Cascadia GeoSciences

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Tectonic land level changes and their contribution to sea-level rise, Humboldt Bay region, Northern California

2017 Final Report

FWS Agreement # 81331BJ244

Award # F11AC01092

http://hbv.cascadiageo.org

Jason R. Patton[1,2], Todd B. Williams[1], Jeff Anderson[3], Tom H. Leroy[4], Kyle Weiss[2], Reed Burgette[5,6], Ed Southwick[2], Whelan Gilkerson[3], Eric Nelson[7], Jay Stallman[1,8], Susan Schlosser[9], Mark Hemphill-Haley[2], Diane Sutherland[1,10], Ray Weldon[6], student volunteers[2,6].

1. Cascadia GeoSciences
2. Humboldt State University
3. Northern Hydrology and Engineering
4. Pacific Watershed Associates
5. New Mexico State University
6. University of Oregon
7. US Fish and Wildlife Service
8. Stillwater Sciences
9. California Sea Grant
10. US Forest Service

The USFWS deliverables as outlined in agreement 81331BJ244 are outlined below. We stipulate the location in the report where these can be found following each deliverable.

1. A complete project description, including, but not limited to: (a) project justification (e.g. limiting factors or watershed assessment); (b) expected biological, ecological, or other benefits; (c) description of all activities; (d) specific measurables of each activity type as appropriate.
    - Introduction section (a), (b), (c)
    - Methods section (c)
    - Contractual Results and Discussion section (d)
2. Schematic diagrams or maps showing the location of the project area and specific work sites. Provide any generated GIS data and map layers pertaining to the project in an electronic format (ESRI ArcGIS compatible).
    - Figures 5, 9, 11, 22, and 23
3. A detailed budget showing how funds were spent compared with the budget estimate in the proposal; include budget shortfalls and overruns in specific line items (and explanations if the differences are significant). The budget shall be in the same format as the estimated budget included in the proposal; identify the amount and type (cash or in-kind service) of matching contributions from the Recipient and all other contributors.
    - Appendix B
4. As appropriate, a CD that contains all the photo points as well as a photo point location map. Each photo point should be marked on the project map, with clear directions to each point.
    - We do not have photo points.
5. As appropriate, type and duration of monitoring (if any), along with an electronic copy (Microsoft Excel compatible) of all collected monitoring and/or assessment data in raw and summarized form.
    - No monitoring is included in this project. However, the Trinidad tide gage data are presented online via the CENCOOS website.

Tectonic land level changes and their contribution to sea-level rise, Humboldt Bay region, Northern California

2017 Final Report

Jason R. Patton[1], Todd B. Williams[1], Jeff Anderson[2], Tom H. Leroy[3]

1. Cascadia GeoSciences jayp@cascadiageo.org toddw@cascadiageo.org

2. Northern Hydrology and Engineering

3. Pacific Watershed Associates

Executive Summary

Land subsidence in and around Humboldt Bay, California contributes to sea-level rise up to 2-3 times greater than anywhere else in California. Sea-level observations and highway level surveys confirm that land is subsiding in Humboldt Bay, in contrast to Crescent City where the land is rising. Rates of sea-level rise are 5.84 mm/yr in South Humboldt Bay (Hookton Slough), 3.76 mm/yr at Fields Landing, 4.61 mm/yr at the North Spit, 2.53 mm/yr at Samoa, and 3.39 mm/yr in Arcata Bay (Mad River Slough). Rates of land subsidence are -3.56 mm/yr in South Humboldt Bay (Hookton Slough), -1.48 mm/yr at Fields Landing, -2.33 mm/yr at the North Spit, -0.25 mm/yr at Samoa, and -1.11 mm/yr in Arcata Bay (Mad River Slough).

Introduction

We submit this report to the US Fish & Wildlife Coastal Program Coordinator as a final report for award F11AC01092 "Tectonic Land Level Changes and their Contribution to sea-level Rise, Humboldt Bay Region, Northern California." This work initiated as, and is a product of, a collaboration of local ecosystem-based managers and scientists, engineers, and geologists collaborating together as volunteers of a working group. The Humboldt Bay Vertical Reference System working group (HumBayVert) began in 2011 and worked towards determining a path to funding a science plan that had potential to address the inconsistency of the Humboldt Bay North Spit tide gage (Eureka, CA) in regards regional sea-level observations in comparison to Crescent City, CA and other continuous gages on the West Coast. Given the discrepancy, one major problem was how to correctly estimate long term sea-level rise estimates in Humboldt Bay compared to the rest of the West Coast. Of particular note, significant effort had been put forth by Jeff Anderson at Northern Hydrology & Engineering identifying and rectifying numerical tide models of Humboldt Bay and associated channels where offsets in tide predictions would occur when utilizing Crescent City tide data versus North Spit tide data.

Our Objectives as Presented in Our Proposal

> This project will characterize the interseismic tectonic land-level change associated with the southern Cascadia subduction zone. Understanding this ongoing phenomenon will allow us to quantify and predict future sea-level trends in northern California. Results from this study will provide fundamental sea- level rise data for making sound management decisions as they apply to managing coastal landscapes and the species and ecosystems that inhabit them, particularly those within the tidal prism, which are the most vulnerable to future sea-level rise . Quantifying future local sea-level change is the first logical step in planning management strategies for coastal ecosystems.

This project furthers the goals of the Service and CA LCC and NPLCC partners by providing scientific and technical support for managing northern California coastal landscapes vulnerable to sea-level rise. This also supports the Humboldt Bay Initiative (http://www.coastalecosystemsinstitute.org/about-hbi/) which includes numerous agencies, managers, and scientists focused on coastal resources management and impacts to these resources. Project work helps to refine knowledge of local and regional variations in the rate of sea-level rise or fall. Land managers will have valuable information to better estimate the trajectory of coastal wetland and upland changes due to changes in sea-level. Completion of this work fills in the last remaining and most southern assessment of this type for the length and scope of the Cascadia subduction zone. This work allows for comparative assessments and cooperative efforts in managing for sea-level rise changes with partners to the north in Oregon and Washington.

Background: Regional Tectonics & Sea-level Observations

We characterize the interseismic plate tectonic land-level change associated with the southern Cascadia subduction zone (CSZ), a major plate boundary fault system in the Pacific Northwest of the United States (**Fig. 1;** Chaytor et al., 2004; Nelson et al., 2006). We utilize tide gage, benchmark level, and Global Positioning System (GPS) observations to evaluate vertical land motion. Results from this study will provide fundamental sea-level rise data for making management decisions as they are applied to coastal landscapes and the species and ecosystems that inhabit the tidal prism, which are the most vulnerable to future sea-level rise (Nichols, 2011; Nichols et al., 2011). Quantifying future local sea-level change is the first step in planning strategies for coastal ecosystems (Church et al., 2011; Horton et al., 2014).

Since the Last Glacial Maximum (LGM; ~22 thousand years ago), global eustatic sea-level has risen ~120 meters (Lambeck and Chappell, 2001; Peltier, 1990, 2002; Peltier and Fairbanks, 2006; Khan et al., 2015). This rise is attributed to natural and anthropogenic forces contributing to melting ice and changes in sea water temperature and salinity (Cazenave and Llovel, 2010). Following 1850, the anthropogenic forcing of Earth's climate has dominated as a control of sea-level rise (Jevrejeva et al., 2009; Stammer et al., 2013). As water and ice masses spatially redistribute, Earth's crust and mantle isostatically adjust to these changes; these viscoelastic isostatic adjustments further contribute to local sea-level (Clark et al., 1978; Gehrels, 2010; King et al., 2012).

The Gorda plate subducts beneath the North America plate at about 36 mm/yr to form the CSZ fault (McCaffrey, 2007; **Figure 1**). When the fault is seismogenically locked, the plate deforms elastically, causing vertical land-level change (Mitchell et al., 1994; Flück et al., 1997; Wang, 2003). Regions directly above the locked region of the fault generally subside during the interseismic period and regions landward of the locked region of the fault generally uplift during the interseismic period, as observed in Japan (Hyndman and Wang, 1995; Loveless and Meade, 2010) and elsewhere (Wang et al., 2001; Feng et al., 2012). Local sea-level change is a sum of the vertical change based on sea-level rise and vertical land-level changes (**Fig. 2**; Nelson et al., 1996; Burgette et al., 2009) and records of prehistoric sea-level can be evaluated by lithostratigraphic and biostratigraphic paleogeodesy (Hemphill-Haley, 1995; Nelson et al., 1996; Atwater and Hemphill-Haley, 1997; Dura et al., 2016). Sources of tectonic deformation also include the northward migrating dextral shear associated with the Pacific-North America San Andreas plate boundary fault system (Williams et al., 2002). Understanding this ongoing tectonic deformation will allow us to quantify and predict future sea-level trends in northern California.

Sea-level rise at the Humboldt Bay North Spit (NS) tide gage is much greater than any other gage in the Pacific Northwest (**Fig. 3**). These NS gage records led some previous researchers to discard these data as apparently anomalous, possibly due to localized site settlement (Mitchell et al., 1994; Verdonck, 2006). National Oceanic and Atmospheric Administration

A

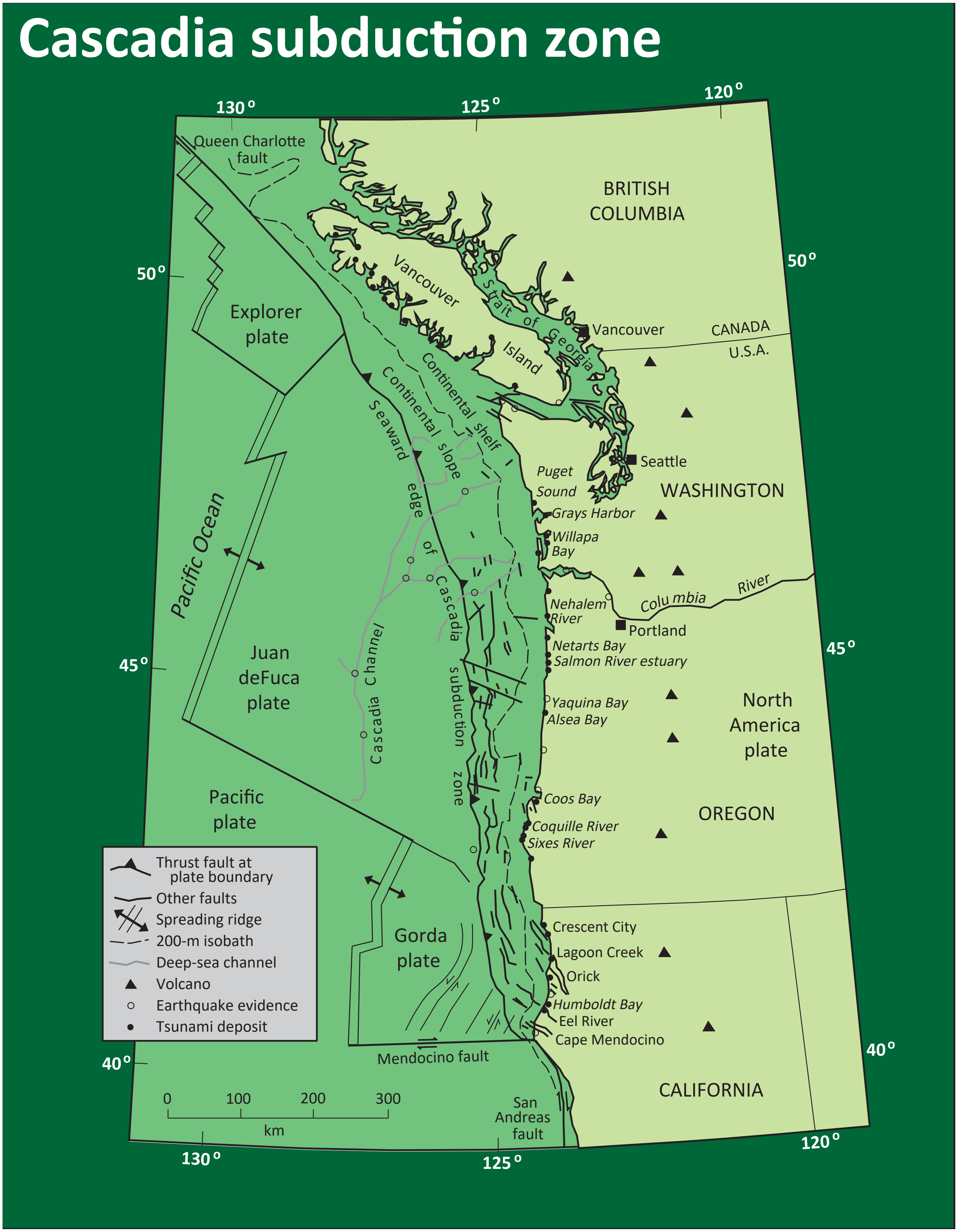
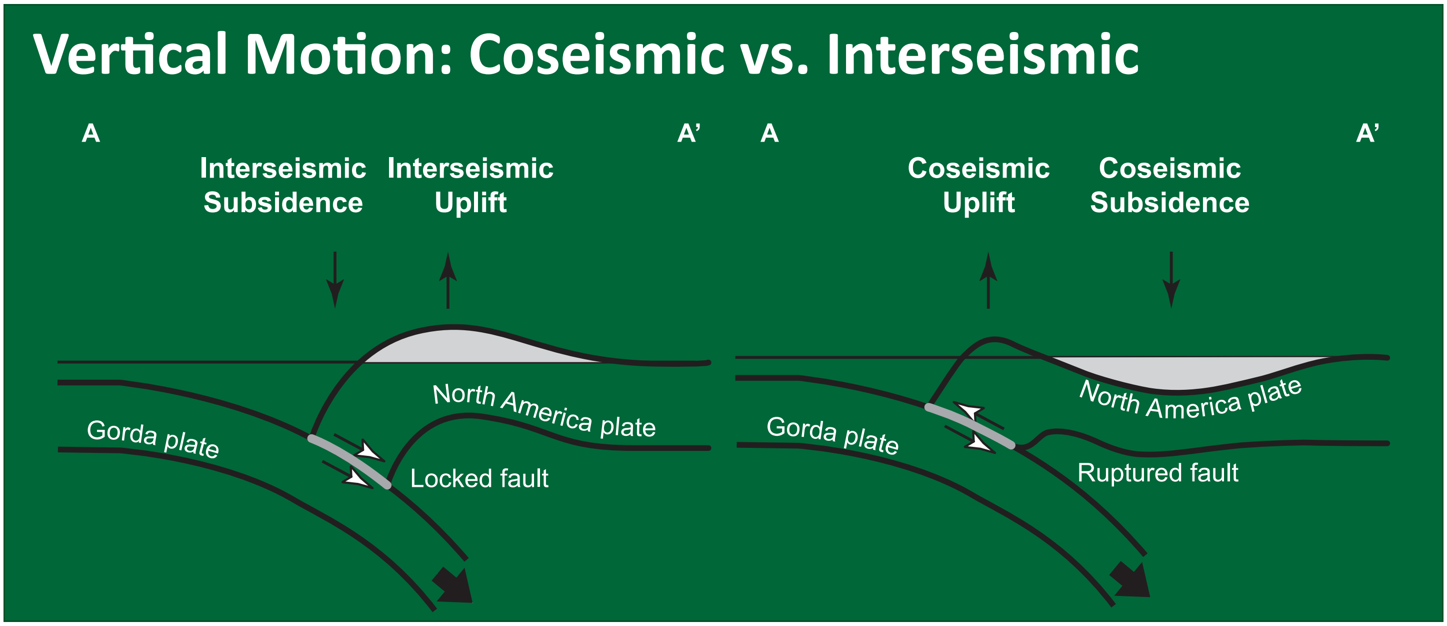


Figure 1. Cascadia subduction zone. A. Tectonic Map shows the plates and their boundary faults. The Cross section of B is designated by the dashed line A-A’ (modified from Chaytor et al., 2004; Nelson et al., 2006). B. Generalized cross section

Figure 1 (cont.)

B



across the subduction zone for the interseismic (in-between earthquakes) and coseismic (during earthquake) periods (modified from Plafker, 1972). The fault is locked during the interseismic period. Interseismic and coseismic vertical motion are inverse of each other.

Center for Operational Oceanographic Products and Services (NOAA Co-Ops) reports an observed sea-level rate of 4.7 mm/yr at the NS tide gage in Humboldt Bay (Fig. 3). However, other researchers include these data in their models of tectonic deformation (**Fig 4**; modified from Wang et al., 2003). Anderson (NHE, 2011) found that tidal models for Humboldt Bay underpredicted tidal elevations by ~1 m when NS tidal data were used as an input to their tidal circulation model.

Sea-level rise in the Pacific Northwest has been estimated to be 2.28 mm/yr (Burgette et al., 2009) and 2.38 mm/yr (Zervas et al., 2013). Based on satellite altimetry, global estimates of sea-level rise range up to 3.4 mm/yr (Cazenave **and**

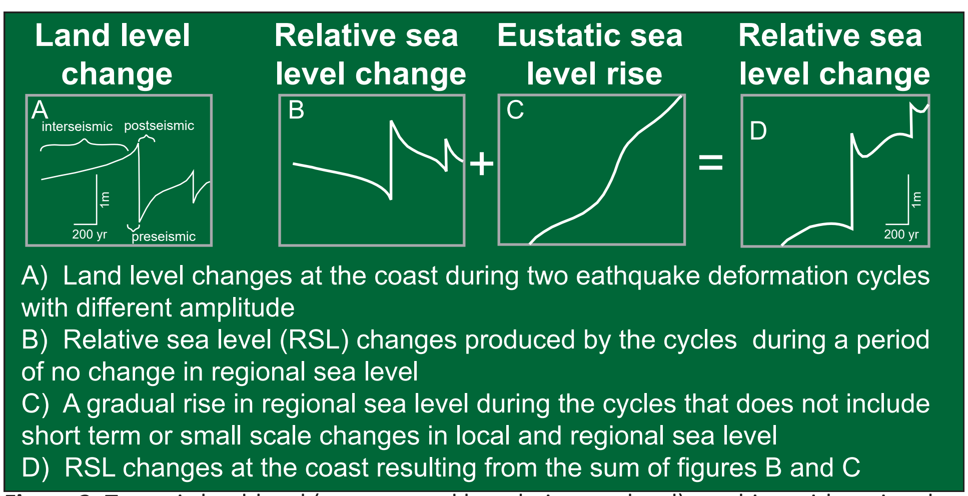


Figure 2. Tectonic land-level (as measured by relative sea-level) combine with regional sea-level rise to result in the water level observations recorded by tide gages (modified from Nelson et al., 1996).

Cascadia subduction zone

Figure 3. West coast sea-level trend variations from NOAA CO-OPS tide gages overlain on a map of the Cascadia subduction zone (modified from Chaytor et al., 2004; Nelson et al., 2006).

Llovel, 2010; Nerem et al., 2010; Wenzel and Schröter, 2014). The discrepancy between regional sea-level rise estimates and the NS tide gage observations suggests that there is subsidence of the land and the associated tide gage. At the next nearest NOAA continuous operating tide gage in Crescent City (CC), California, sea-level is observed to be lowering at 0.65 mm/yr (Zervas et al., 2013), the result of upwards vertical land motion in Crescent City. When the NS tide gage was installed, 11 tidal benchmarks and associated temporary gaging stations were deployed from 1977 to 1980.

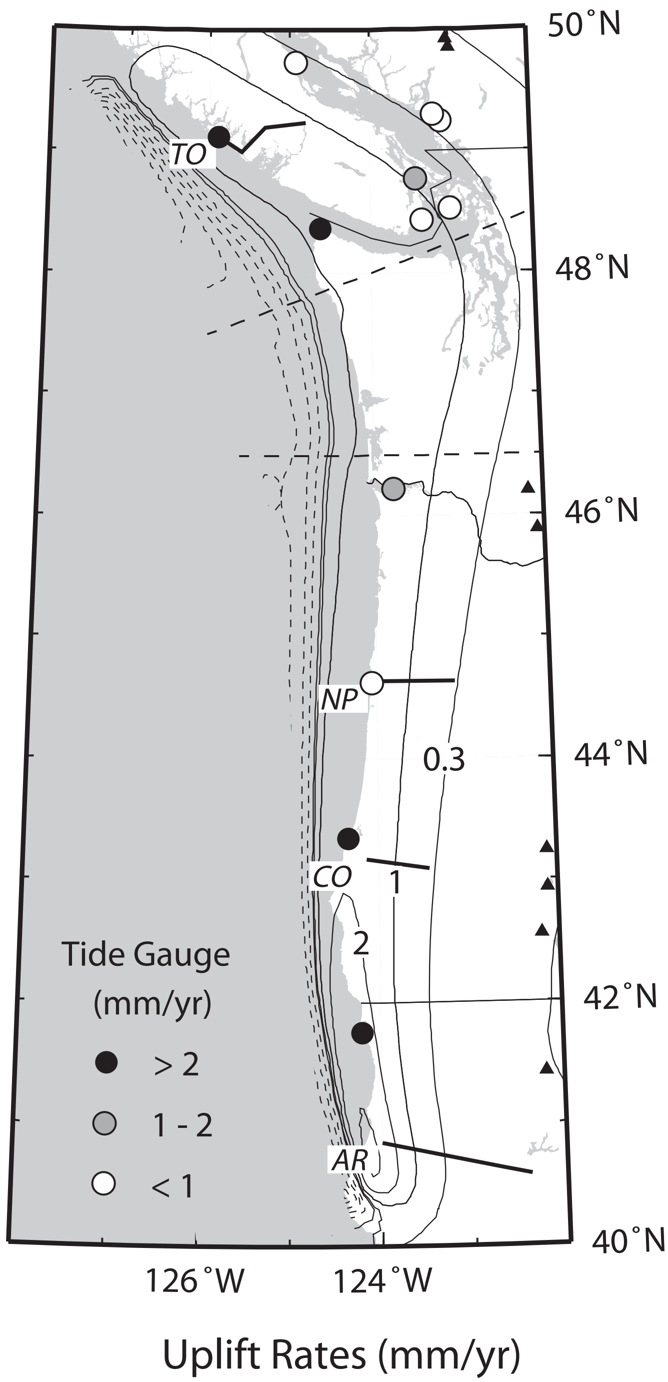


Figure 4. Uplift Rates modeled by Wang et al. (2003) for the Cascadia subduction zone. Contours are in mm/yr. Tide gage ReSLR rates are plotted as designated by the legend. Humboldt Bay is in the region of largest uplift rate for the entire subduction zone.

Utilizing a subset of these initial observation points, we analyze contemporary sea-level observations in Humboldt Bay to investigate Local sea-level rise relative to Regional sea-level rise. We also use first order leveling data collected by the National Geodetic Survey (NGS) to determine vertical land motion rates for the second half of the twentieth century (Burgette et al., 2012). Finally, we incorporate continuous GPS observations into our analyses of vertical land motion for the past decade (USGS, 2016).

Methods

We utilize water level observations in Humboldt Bay (North Spit, NS; Mad River Slough, MRS; Samoa, SO; Fields Landing, FL; Hookton Slough, HS), Trinidad, and Crescent City as collected by the National Oceanic and Atmospheric Administration (NOAA; 1972-1989), US Army Corps of Engineers San Francisco Office (USACE; TOWILL, 2011), and Northern Hydrology and Engineering (NHE; 2008, 2012-13, 2016) to evaluate local trends in sea-level compared to Crescent City, the longest operating tide gage in the region (1933-present; **Fig.5)**. We installed tide gages within the Humboldt Bay National Wildlife Refuge, Salmon Creek Unit, Hookton Slough (**Fig.5**), Mad River Slough, and at the Trinidad Pier. We use available first-order leveling data collected by the NGS predominantly along the route of Highway 101 from Cres-

cent City south through the Humboldt Bay region (Fig.5). We also use GPS observations analyzed by the United States Geological Survey (USGS) from continuous GPS sites (cGPS) operated by the National Science Foundation's EarthScope program. We combine these nearshore water-level and onshore land-level observations to determine the land-level and sea-level trends around Humboldt Bay.

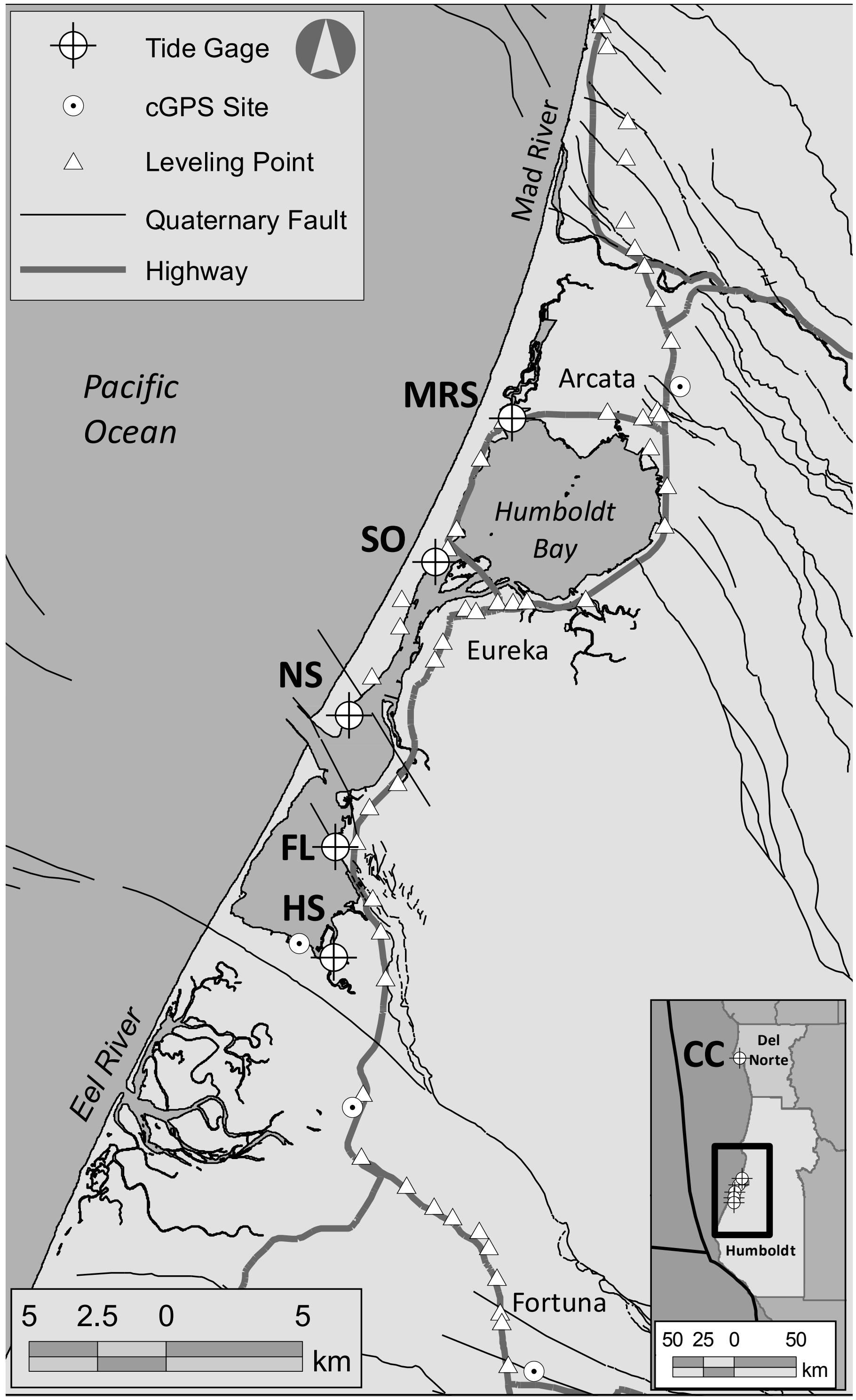


Figure 5. Geodetic Site Map. Tide gage, cGPS, and benchmark leveling point locations are displayed by symbols as designated in the legend. Tectonic faults from the USGS Active Fault and Fold Database are plotted as black lines. Crescent City is plotted in the inset map.

The Methods as Presented in Our Proposal

A combination of near shore water-level and onshore land-level surveys will be utilized to determine the tectonic land level changes and sea-level trends around Humboldt Bay.

Tide Gages

We analyze water level observations at tide stations for CC, TR, and five locations in Humboldt Bay (NS, MRS, SO, FL, and HS) to estimate the relative sea-level (RSL) and vertical land motion (VLM) rates at these sites (**Fig.5**). RSL and VLM rate estimates for CC were determined directly from the water level observations due to the long record length (81 years). All of the tidal observations in Humboldt Bay are considered too short (less than 40 years) to allow direct estimates of RSL and VLM rates (**Table 1**). Rates for these sites were determined following the general approach of Burgette et al. (2009), which uses the rates determined for the long-term CC site and the relative rates of differencing the short-term records in Humboldt Bay to the CC data. All rates were determined using least squares linear regression of the time series data.

Table 1. Observation Spans for Tide Gages

Water Level	Beginning Observation	End Observation	Observation Span
Crescent City	1933	2013	80
Trinidad	1972	1989	17
Mad River Slough	1978	2008	30
Samoa	1978	2011	33
North Spit	1977	2013	36
Fields Landing	1978	2011	33
Hookton Slough	1978	2011	33

Previous estimates of RSL and VLM rates for CC used the long-term monthly mean sea-levels with the average seasonal cycle removed (Burgette et al., 2009; Zervas, 2009 and 2013). Recently, Komar et al. (2011) demonstrated that using the annual summer water levels provided the statistically best RSL trends for the Pacific Northwest coast. The annual summer water levels consist of the 3 month average centered on the unadjusted minimum monthly summer value.

Both the long term monthly mean (Burgette et al., 2009; Zervas, 2009 and 2013) and the 3-month summer mean (Komar et al., 2011) approaches were used to estimate the RSL rates for the CC and NS data and the relative VLM of the differencing technique of NS minus CC.

Crescent City (CC)

There is a continuous tide gage operated by NOAA, located on the Citizens Dock. This gage has been operating since 4/10/1933. NOAA posts the historic and modern water surface elevation data on their website. We use data that temporally overlap with data collected at the NS gage (beginning 8/16/1977).

https://tidesandcurrents.noaa.gov/stationhome.html?id=9419750

Trinidad (TR)

NOAA collected data at the "old" Trinidad Pier (pre-2012) from 1972-1989. We utilize water surface elevation data collected by NOAA. These data are posted on their website. The Central and Northern California Ocean Observing System (CENCOOS) operated a tide gage / water quality sonde at this location between 2005 and 2011. These data are available upon request from CENCOOS. When the new Trinidad pier was constructed in 2012, a new gage was installed. The precision of this gage is too low for the analyses that we use, therefore, we installed a new tide gage adjacent to it in 2016. These observational data are published online via the CENCOOS website.

http://www.cencoos.org/data/shore/trinidad

The Stilling basin design we used is based upon the existing CENCOOS design (**Fig. 6**). We used 1" wide stainless steel strapping to connect the stilling basin to the existing 12" diameter ABS plastic piling (**Fig. 7**). The stilling basin is composed of Kanaflex™ 4 inch diameter plastic tubing. The YSI tide gage will hang on a stainless steel wire within the still-

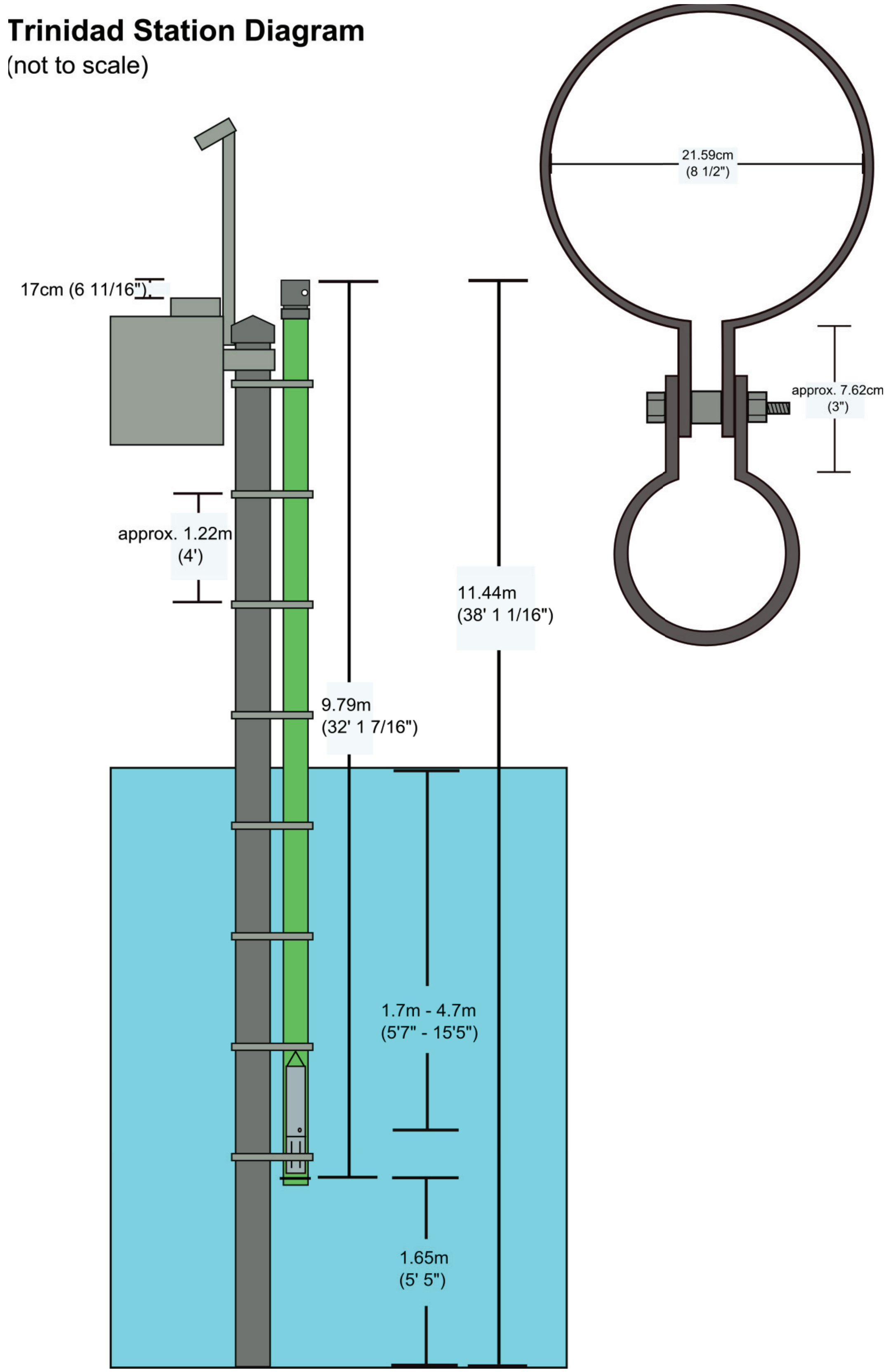


Figure 6. Stilling basin design is based on an existing design from CeNCOOS. There is a 4" diameter flexible plastic pipe that is attached to the ABS piling. There are 7 stainless steel brackets connecting these two pipes. The actual as-built design is slightly different.

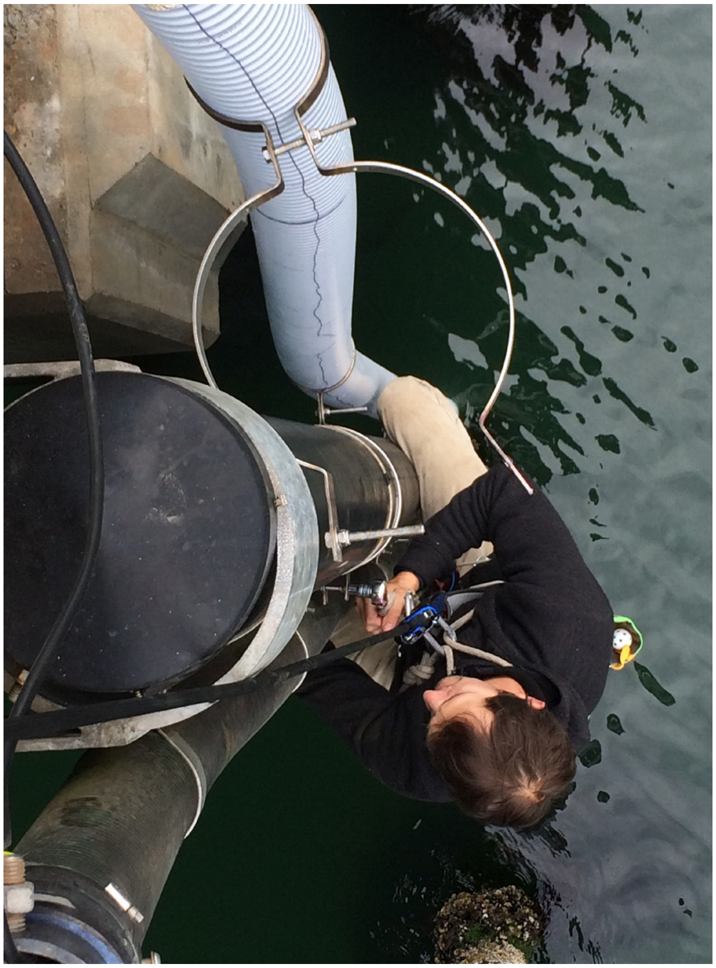


Figure 7. Stilling basin being attached to the black piling. The existing CENCOSS tide gage is on the north side of the piling and the new HBV stilling basin is attached to the south side of the piling.

Figure 8. Stilling basin with stainless steel straps attached. The base of the basin is closest to the photographer. Note the two 5/8" bolts just above the lowest strap.

ing basin. There are two 5/8" diameter bolts near the base of the basin that the gage will rest upon (Fig. 8). We drilled several ¾" holes at the elevation of the gage so that the water will be able to circulate within the basin. This will keep the salinity measurements more accurate.

We conducted a first order elevation survey on Monday August 1, 2016 (**Fig. 9**). We used a Trimble NiMi digital level with 0.3 mm vertical precision (Fig. 10). Our survey loop brought vertical elevation control from the National Ocean Service tidal benchmarks 9059 L and 9059 M to several bolts that are attached to the pier. We conducted a second survey between these bolts and the two stilling basins (CENCOOS and HBV). The closure errors for these two surveys are 0.00047 and 0.00000 mm, respectively.

We installed a YSI 600LS vented Level Sonde that includes a temperature sensor. Prior to installation we calibrated the sonde in sea water with a depth of 1 meter. The sonde is installed to a position that sits above the two 5/8" stainless steel bolts, so the data from this sonde are referenced to an orthometric elevation via the high precision elevation survey. The sonde is connected via a cable to the CENCOOS data collection infrastructure. The tide gage data are then trans-

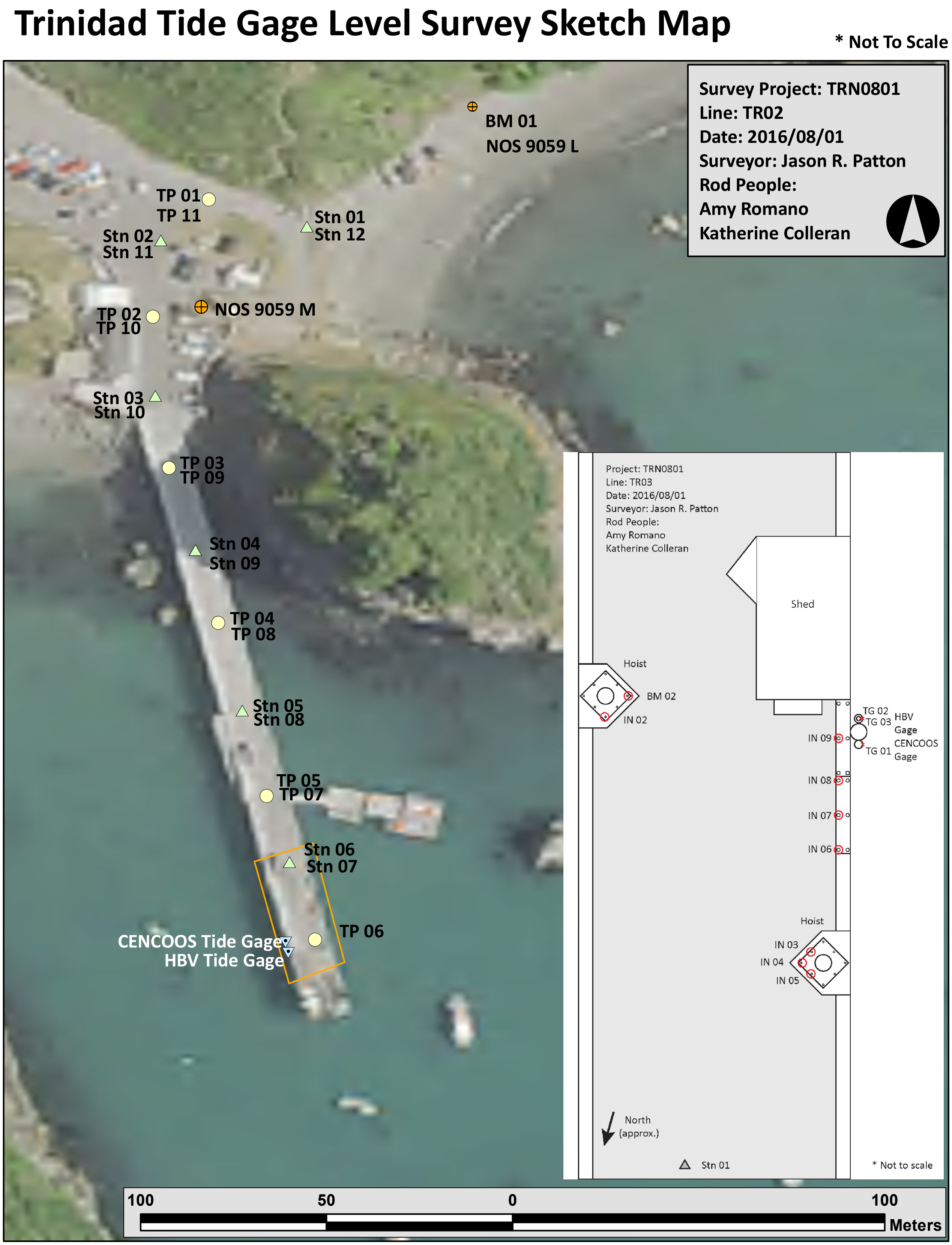


Figure 9. Map showing benchmark (orange circles), turning point (yellow circles), and instrument locations (green triangles). The two tide gage locations are marked as light blue triangles. The inset map shows large scale locations of bolts that are surveyed and can provide elevation control for future surveys. The inset map location is marked approximately by the orange polygon. The shed contains the electrical and communications infrastructure for real-time connectivity for the tide gage data.

mitted electronically and published online via the CENCOOS website. These data collected by this new tide gage are not incorporated into any analyses to date. We limit our analyses to the existing CENCOOS tide gage data.

Figure 10. Photo of digital level and student volunteers.

Mad River Slough (MRS)

This tide gage location was operated intermittently by NOAA from September 1977 – November 1979. Northern Hydrology and Engineering initially operated a gage upstream of the HWY 255 Bridge in 2008 for the purposes of establishing tidal wetland geometric relations (i.e. tidal geometry) in Mad River Slough (NHE, 2009). Later we deemed it necessary to install a gage closer in proximity to the location of the 1970's observations. Jeff Anderson and staff from Northern Hydrology and Engineering recently concluded operating a tide gage near the Mad River Slough Highway 255 Bridge (2016). The stilling basin was located near the east side of the active channel.

For the 2008 observations (which we use in our analyses) NHE installed some temporary benchmarks to provide survey control for the water surface elevation observations. Five benchmarks (½-inch rebar) were installed and surveyed into a vertical and horizontal control network using a Real Time Kinematic (RTK) Global Positioning System (GPS), based on National Geodetic Survey (NGS) benchmarks W 1091 and J 735 (Figure 3-1 in NHE 2009). California Department of Transportation (CalTrans) Benchmark HUM-255 R5.26R was used to verify the NGS benchmarks.

Water level data were measured at 6-minute intervals with Solinst 3001 water level loggers. Two stations were established in the main stem of MRS: (1) MRS South Station was located 1,200 feet downstream of the tidal geometry project site, approximately 2,300 feet upstream of the slough mouth at Highway 255/Samoa Boulevard Bridge; and (2) MRS North Station was located 1,100 feet upstream of the project site (Figure 3-1 in NHE 2009). Stations were established at different locations in the slough channel to determine the degree of tidal amplification and peak time lag occurring within MRS. Data was collected for seven months at the MRS North Station and three months at MRS South Station. The shorter data record at the MRS South Station is due to vandalism of the pressure transducer. Measured data were translated to water surface elevation and were reduced to equivalent 19-year tidal datums through a mathematical comparison with the closest control station at NOAA Station ID 9418767 (North Spit) using the NOAA direct method computational technique (NOAA, 2003) (Table 4-1 in NHE 2009).

We conducted a first order level survey in August, 2016. We used a Trimble NiMi digital level with 0.3 mm vertical precision. Our survey loop brought vertical elevation control from the NOAA Mad River Slough benchmark J735 1944, reset in 1970 by the Northwest Pacific Railroad (NWPRR). The benchmark is in a concrete wall on the southern side of the western end of the railroad bridge that crosses the Mad River Slough. The closure errors range from 0.1 to 0.35 mm.

NHE acquired data for two monthly MSL observations for the years 2008 and 2016. These data are insufficient to determine average seasonal or average summer MSL data, so we rely on the unadjusted data.

Samoa (SO)

This tide gage location was operated by NOAA from May 1978 – January 1979. The US Army Corps of Engineers (USACE) contracted with Towill Engineering to collect tide gage observations at this site from December 2010 – February 2011. USACE San Francisco Office released the data to this project in 2013 and NOAA subsequently published these data online.

North Spit (NS)

This is a tide gage operated by NOAA and has been operating continuously since 8/16/1977. NOAA posts the historic and modern water surface elevation data on their website. These are the data that we utilize in our analyses.

https://tidesandcurrents.noaa.gov/stationhome.html?id=9418767

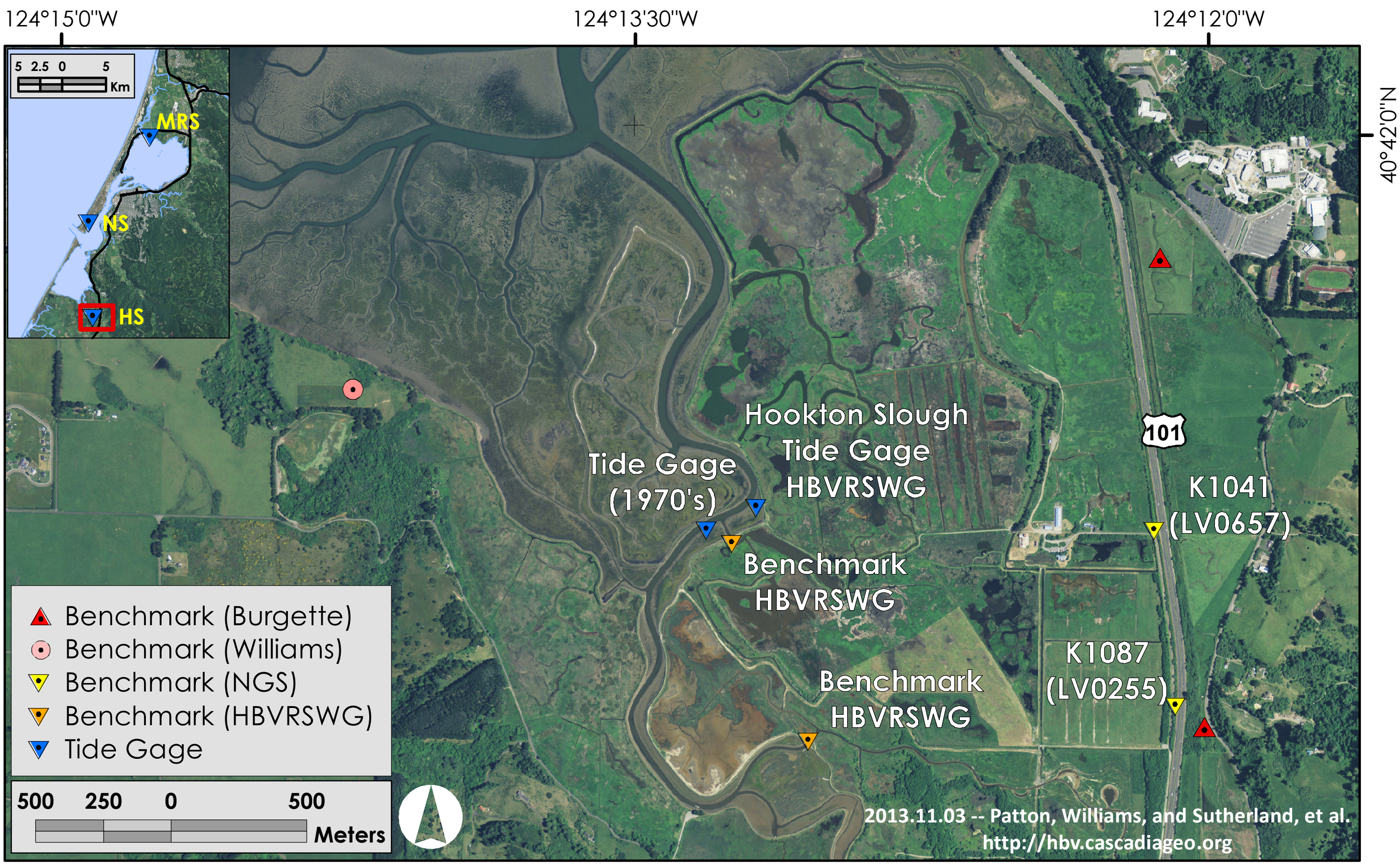
Fields Landing (FL)

This tide gage location was operated by NOAA from November 1978 – January 1979. The USACE contracted with Towill Engineering to collect tide gage observations at this site in 2011. USACE San Francisco Office released the data to this project in 2013 and NOAA subsequently published these data online.

Hookton Slough (HS)

This tide gage location was operated by NOAA from October 1977 – May 1979. We deployed a temporary tide gage at the Humboldt Bay National Wildlife Refuge and Sanctuary, Salmon Creek Unit, from August, 2012 to November, 2012. Two WL16 Titanium Global Data Loggers (logger) were installed in Hookton Slough on 2 August 2012 (**Fig. 11 A**).The gage site was located on a the outside of a large bend adjacent to the levee road, approximately 120 m west of the Long Pond Tide Gate, and about 45 meters west of the historic NOAA tide gage site. Access to the gage site is from the Humboldt Bay National Wildlife Refuge Salmon Creek Unit. The loggers are recording at 6 minute intervals and in depth units of meter to 3 significant figures (i.e. readings to the nearest millimeter).

A



B

Figure 11. Hookton Slough Tide Gage. A. Location Map Hookton Slough Tide Gage. B. Tide gage installation site photo.

The logger computers are housed in an electric breaker panel box that is fastened to a metal fence t-post (FP) that was installed in the rock slope protection along the bank of the slough channel (**Fig. 11 B**).The logger pressure transducers are housed in individual PVC stilling wells that are fastened with stainless steel pipe clamps to a vertical FP. The vertical fence post is fastened near the top with pipe clamps to a diagonal fence post for stability. Two buoys were attached to separate FP installed up and down of the two loggers to mark their location in the slough channel.

Five FP were installed adjacent to the loggers at different elevations to serve as staff plates. The five FP were surveyed using an engineering level to a temporary bench mark on an assumed vertical datum. The temporary bench mark is an approximate 1.3 m piece of rebar installed into the ground across the levee road from the gage site. The temporary bench mark can serve as a future reference bench mark for detailed level surveying to be conducted in the future, and to aid in verifying staff plate and logger stability.

The staff plates (FP) are used to calibrate/convert the logger depth data to water surface elevation by measuring the distance from the top of the FP to the water surface. Calibration points and simultaneous logger readings were collected on the day of installation during a low to high tidal cycle. Additional calibration data is collected during each operation and maintenance site visit.

Prior to installation, the loggers were recalibrated between 0 and about 4 meters. Although the loggers are recording to 3 significant digits the WL16 Global Data Loggers are not that accurate. The stated accuracy of the Global loggers is 0.1% of the full scale range at constant temperature, and 0.2% of full scale range over 35 to 70 degrees Celsius. The full scale range on these loggers is approximately 4.6 m (15 ft) thus the accuracy is between 4.6 and 9 mm.

Benchmark Leveling

We analyze the available first-order leveling data collected by the NGS, which were collected in 1931, 1945, 1968, and 1988. We analyzed the unadjusted line data, with orthometric, rod, level, temperature, astronomical, refraction, and magnetic corrections applied by the NGS as appropriate (Federal Geodetic Control Committee, 1984). The 1931 data pre-date the installation of the NS tide gage and the surveyed benchmarks are confined to the route of Highway 101 between Crescent City south through the Humboldt Bay region. We also analyzed data from a spur route between Highway 101 and the NS tide gage that was first observed in 1945 as well as the regional lines observed in 1968 and 1988. We calculated tilt rates relative to Benchmark 60 in the Eureka downtown, which has a long history and appears to be locally stable. Run distance-dependent one sigma errors are propagated following the procedure of Burgette et al. (2009).

GPS

Continuously operating Global Positioning System (CGPS) position reports and station velocity estimates were sourced from the USGS. CGPS stations operated by the National Science Foundation's EarthScope – Plate Boundary Observatory (PBO) project, operated and maintained by UNAVCO, Inc., provide an independent data set to determine rates of vertical land motion. Data presented from these GPS stations are in the ITRF 2008 reference frame, which is a global reference frame with respect to the GPS constellation, and reflects the absolute motion of the station (relative to the center of mass of Earth) and is not biased from any other external reference (**Fig. 12**). We acquired the latest GPS data from the USGS to include in our data product summary (year downloaded).

Data Results

Here we present the results from (1) the tide gage observations and analyses, (2) the benchmark analyses, and (3) the GPS observations and analyses.

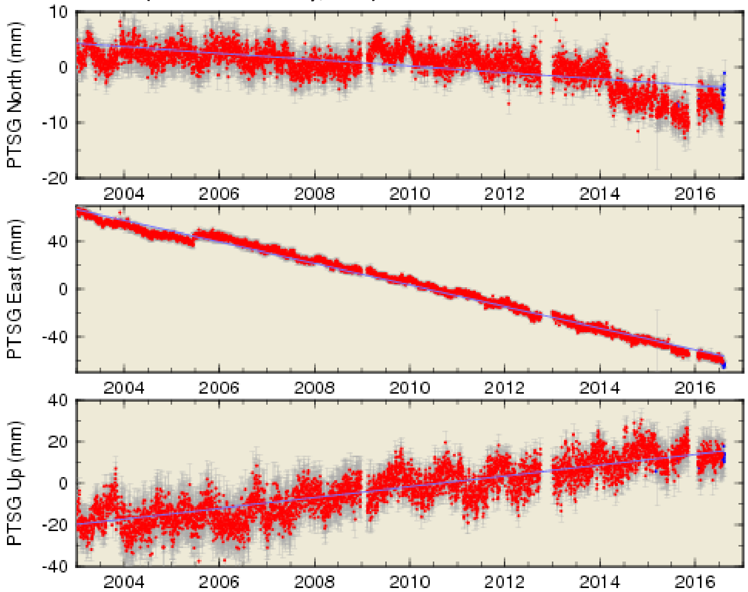
Tide Gage

We here present a summary of sea-level observations made at tide gage locations in northern California (**Table 2)**. Jeff Anderson at Northern Hydrology & Engineering re-evaluated the data by removing the seasonal cycle or using summer values for a relative SLR estimate. Anderson (JKA) provides his recommendation for each data set in the notes column of Table 2. Sea-level rise (SLR) and vertical land motion (VLM) rates incorporate a eustatic sea-level rise rate (regional sea-level rise rate, ReSLR) to calculate the relative sea-level rise rate (RSLR) for each location. Rates for each study location are differenced from Crescent City (sta-CC), which has the longest sea-level observations. These differences result in an estimate of vertical land motion (VLM) with upwards in the positive direction (e.g. the Crescent City tide gage location is rising vertically at 3.25 mm/yr and the Trinidad tide gage location is sinking vertically at 0.87 mm/yr). We present our estimates for the RSL rates using the long term monthly mean (Burgette et al., 2009; Zervas, 2009 and 2013) and the 3-month summer mean (Komar et al., 2011) approaches for the CC and NS data (Figs. 13 and 14) and the relative VLM of the differencing technique of NS minus CC (**Fig. 15**).

Crescent City (CC)

Monthly MSL for the period of 1933-2013 is -0.92 mm/yr. The monthly MSL, with the seasonal cycle removed, for the period of 1933-2013 is -0.97 mm/yr. We present RSL and VLM data for CC in **Table 2.**

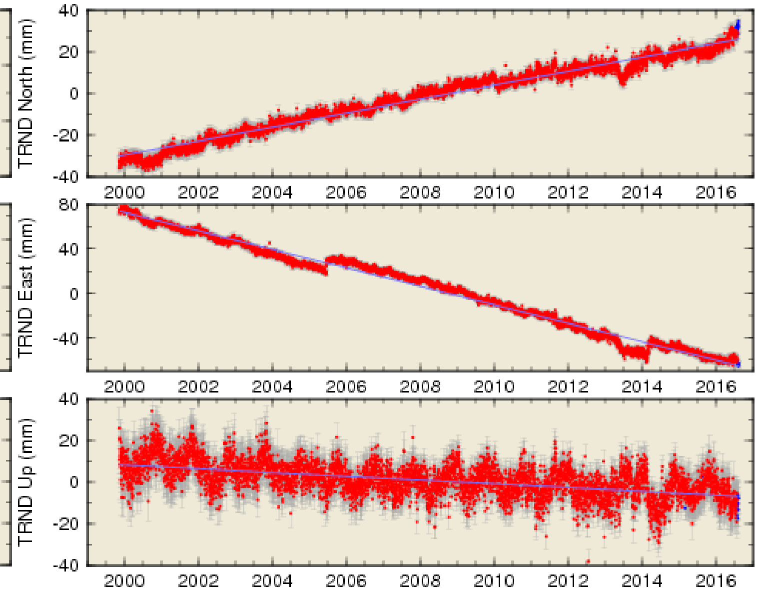
A. PTSG (Crescent City, CA)



Plot Last Updated: Thursday, August 11, 2016 07:02:46 PDT

	Velocity (mm/yr)	Uncertainty (mm/yr)	RMS (mm)
North	-0.60	0.30	2.52
East	-9.10	0.30	3.29
Up	2.60	0.30	6.39

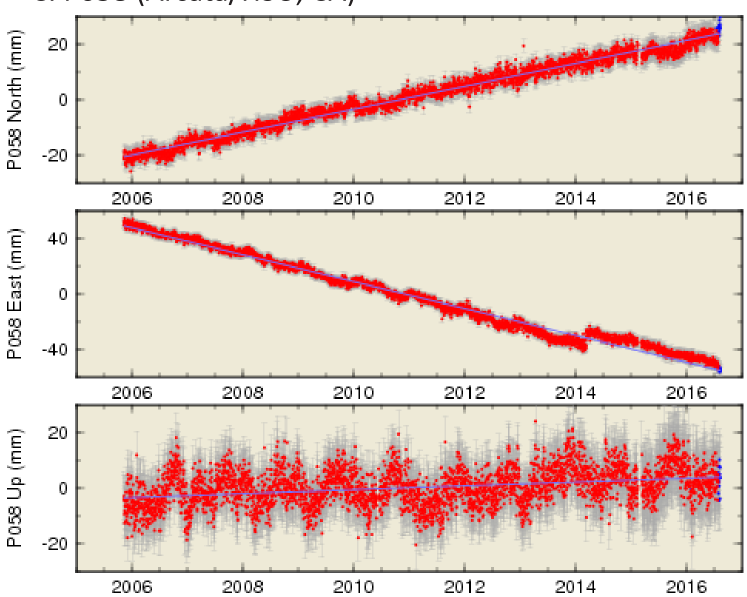
B. TRND (Trinidad, CA)



Plot Last Updated: Thursday, August 11, 2016 07:02:54 PDT

	Velocity (mm/yr)	Uncertainty (mm/yr)	RMS (mm)
North	3.30	0.20	2.75
East	-8.30	0.20	4.73
Up	-0.90	0.20	6.54

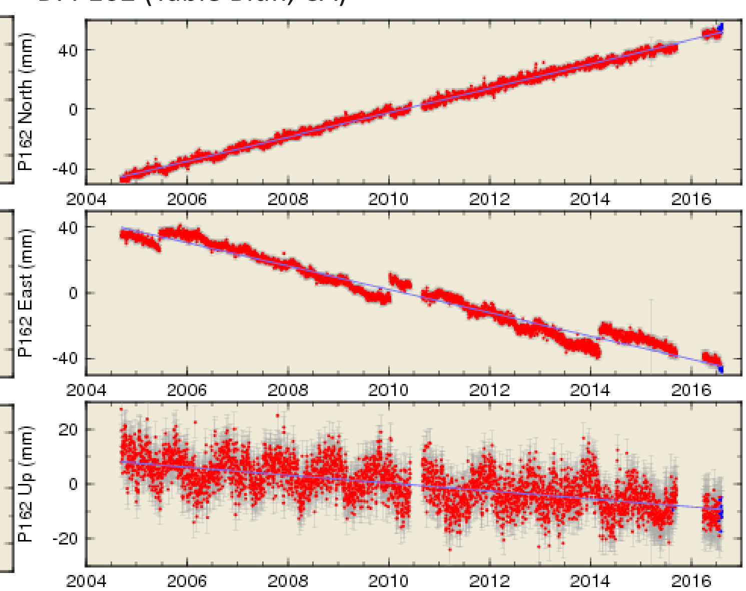
C. P058 (Arcata/HSU, CA)



Plot Last Updated: Thursday, August 11, 2016 07:00:51 PDT

	Velocity (mm/yr)	Uncertainty (mm/yr)	RMS (mm)
North	4.10	0.30	1.78
East	-9.70	0.30	3.49
Up	0.70	0.30	6.03

D. P162 (Table Bluff, CA)



Plot Last Updated: Thursday, August 11, 2016 07:01:06 PDT

	Velocity (mm/yr)	Uncertainty (mm/yr)	RMS (mm)
North	8.20	0.30	1.76
East	-7.10	0.30	4.48
Up	-1.50	0.30	5.90

Figure 12. USGS published GPS observations relative to the International Terrestrial Reference Frame (ITRF2008) a 2008 derived datum for the International Terrestrial Reference System (ITRS). The ITRF is a reference system used by geodesists that assumes no tectonic motions from plate tectonics. More can be found here https://www.iers.org/IERS/EN/Science/ITRS/ITRS.html. Velocities are shown in a table below each plot. (A) Point St. George, Crescent City, CA (PTSG); (B) Trinidad Head, CA (TRND); (C) Arcata/Humboldt State University, CA (P058); and (D) Table Bluff, CA (P162)

Trinidad (TR)

Monthly MSL for the period of 1972-1989 is 3.15 mm/yr. TR MSL, referenced to CC, for the period of 1972 – 1989 is 4.12 mm/yr (**Fig. 16**). We present RSL and VLM data relative to CC in **Table 2.**

Mad River Slough (MRS)

Monthly MSL for the period of 1978-2008 is 3.39 mm/yr. Using only the 2008 observations, MRS MSL, referenced to CC, for the period of 1978/1979 – 2008 is 4.36 mm/yr (**Fig. 17**). We present RSL and VLM data relative to CC in **Table 2.**

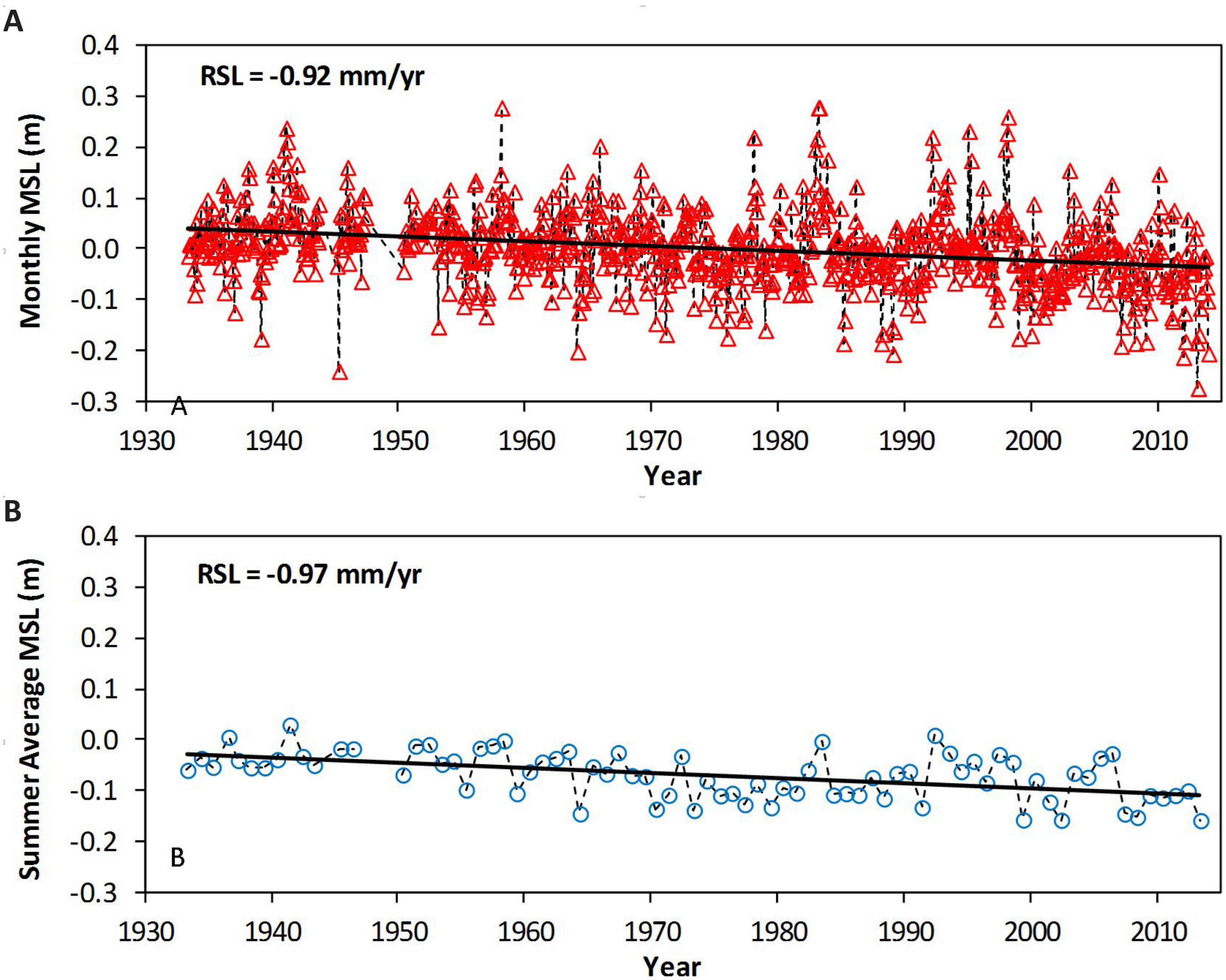


Figure 13. Tide gage results. Crescent City NOAA tide station (9419750) relative sea level trends using monthly mean sea levels with the average seasonal cycle removed (A), and summer 3-month average mean sea levels (B).

Samoa (SO)

Monthly MSL for the period of 1978-2016 is 2.53 mm/yr. SO MSL, referenced to CC, for the period of 1978/1979 – 2010/2011 is 3.50 mm/yr (**Fig. 18**). NS MSL, referenced to CC for the same period available for SO is 5.49 mm/yr. We present RSL and VLM data relative to CC in **Table 2.**

North Spit (NS)

Monthly MSL for the period of 1977-2013 is 3.85 mm/yr. The monthly MSL, with the seasonal cycle removed, for the period of 1977-2013 is 4.70 mm/yr (**Fig. 14**). NS monthly MSL relative to CC is 5.58 mm/yr. We present RSL and VLM data relative to CC in **Table 2.**

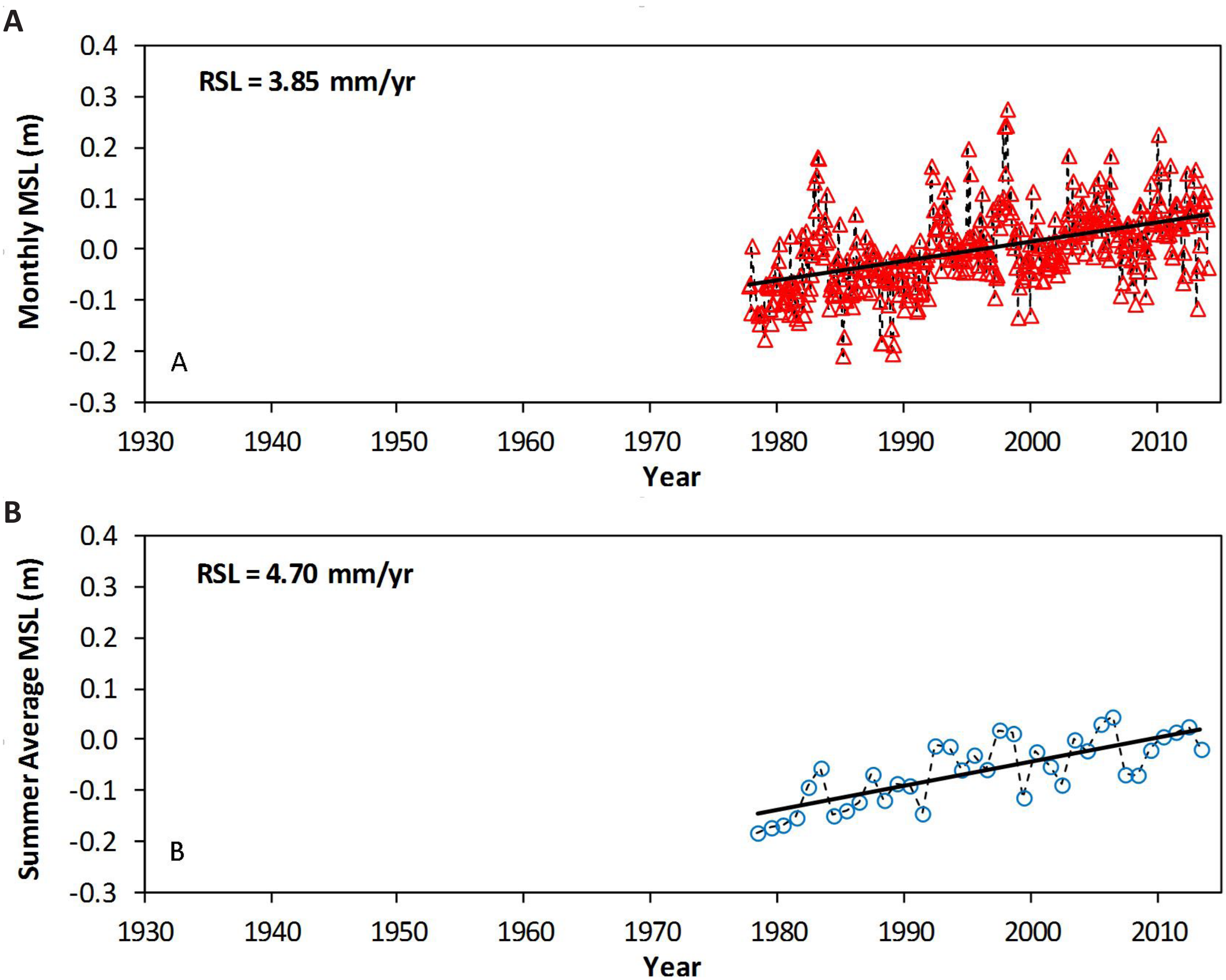


Figure 14. Tide gage results. North Spit NOAA tide station (9418767) relative sea level trends using monthly mean sea levels with the average seasonal cycle removed (A), and summer 3-month average mean sea levels (B).

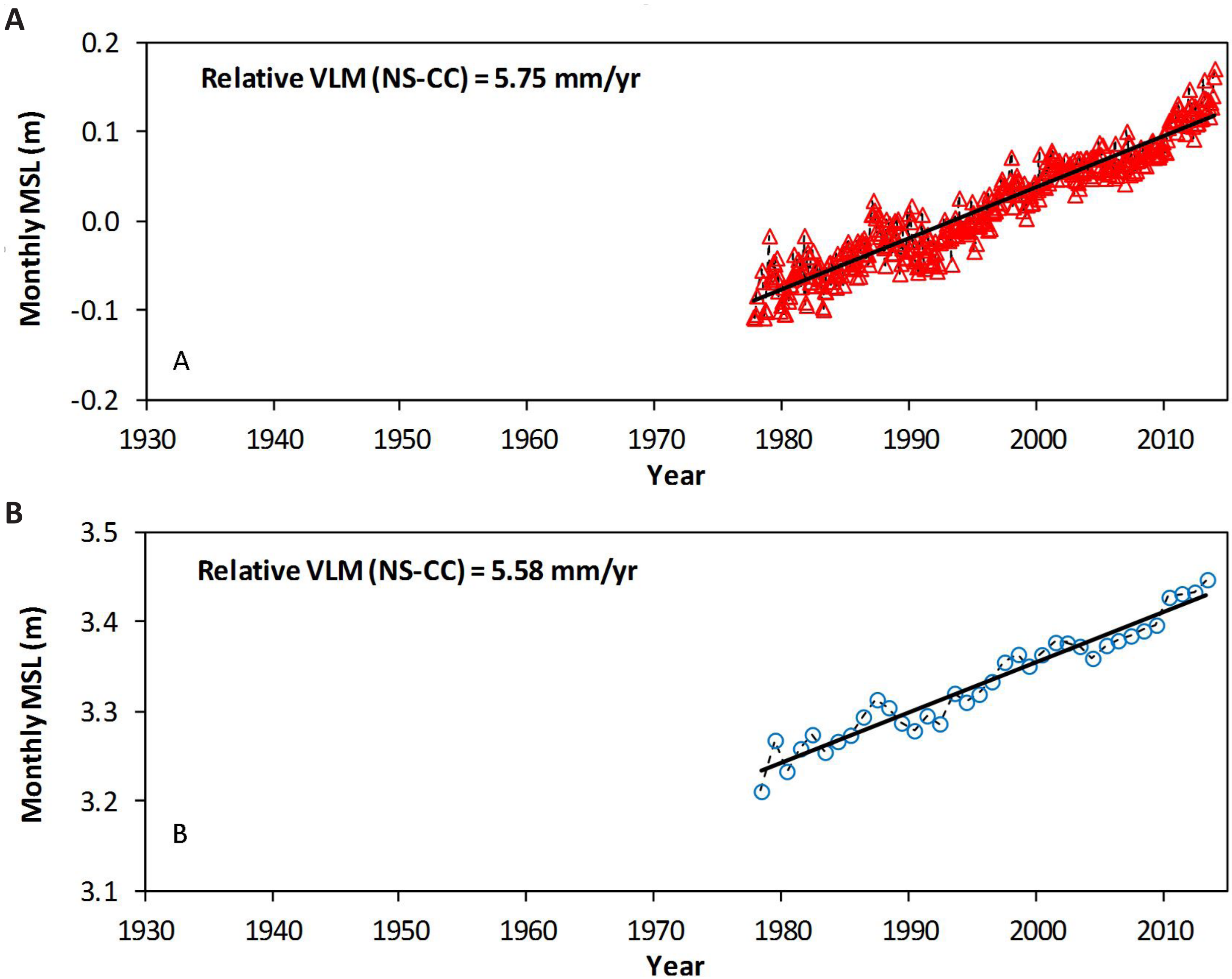


Figure 15. Differenced time series (North Spit minus Crescent City) representing the vertical land motion rate of North Spit relative to Crescent City using the monthly mean sea levels with the average seasonal cycle removed (A), and summer 3-month average mean sea levels (B).

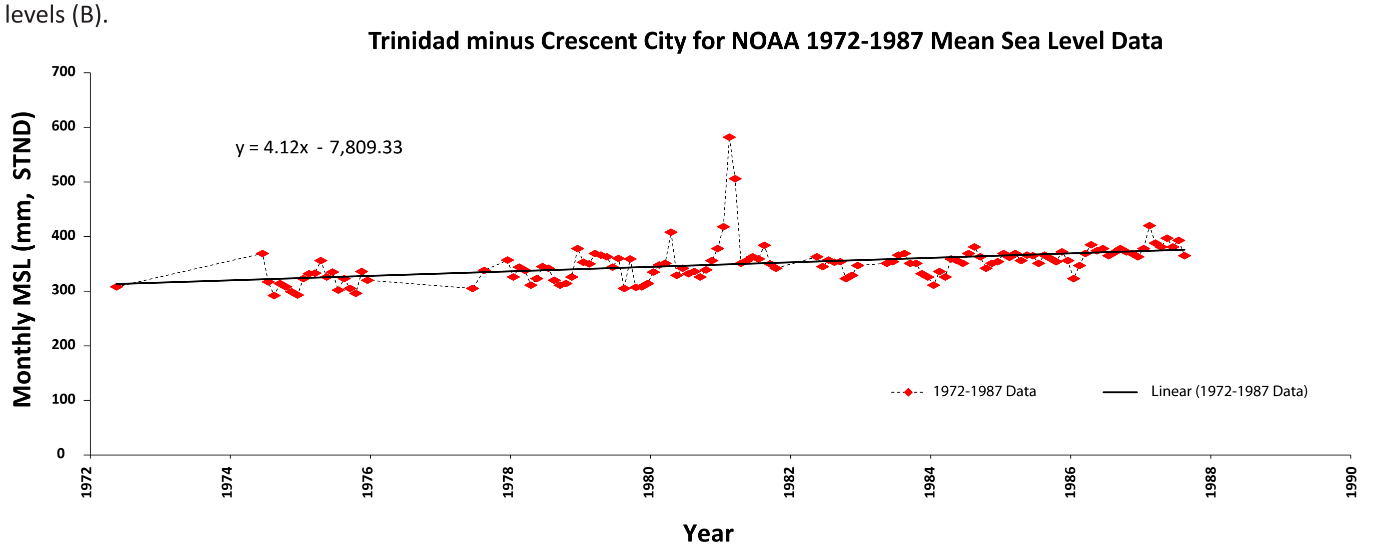


Figure 16. Differenced time series (Trinidad minus Crescent City) representing the vertical land motion rate of Trinidad relative to Crescent City using the monthly mean sea levels.

Fields Landing (FL)

Monthly MSL for the period of 1978-2016 is 3.76 mm/yr. FL MSL, referenced to CC, for the period of 1978/1979 – 2010/2011 is 4.45 mm/yr. NOAA published a rate for the same period of 1978/1979 – 2010/2011 at 4.73 mm/yr (**Fig. 19**). NS MSL, referenced to CC for the same period available for FL is 5.64 mm/yr. We present RSL and VLM data relative to CC in **Table 2.**

Hookton Slough (HS)

Monthly MSL for the period of 1978-2012 is 5.84 mm/yr. HS MSL, referenced to CC, for the period of 1978/1979 – 2012 is 6.81 mm/yr (**Fig. 20**). NS MSL, referenced to CC for the same period available for SO is 5.77 mm/yr. We present RSL and VLM data relative to CC in **Table 2.**

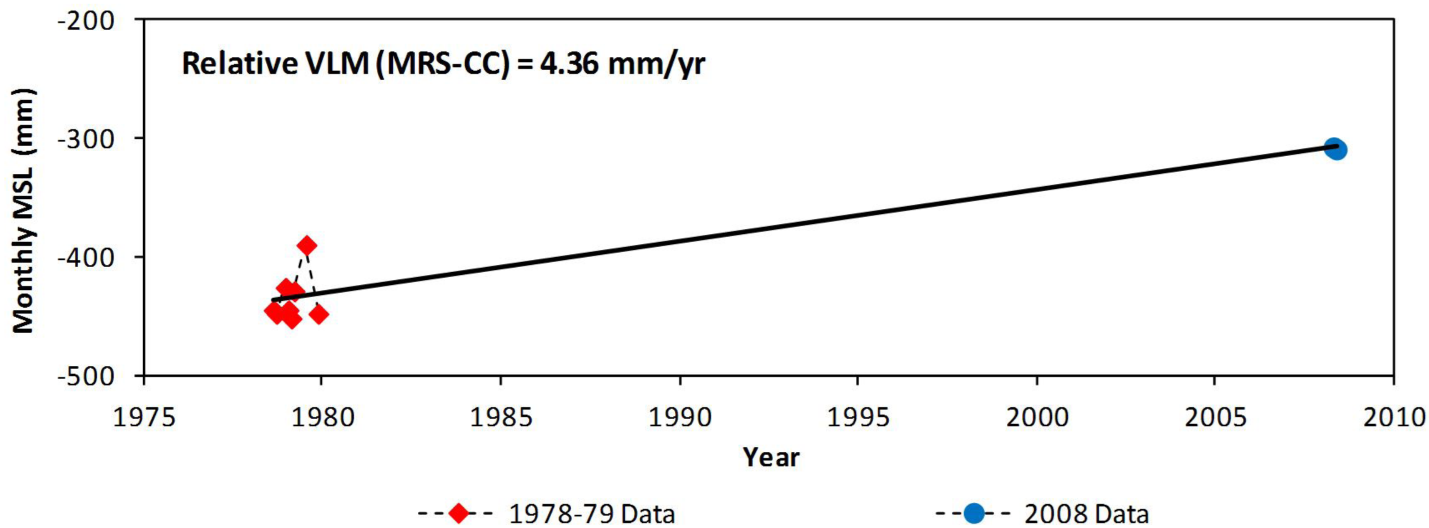


Figure 17. Differenced time series (Mad River Slough minus Crescent City) representing the vertical land motion rate of Mad River Slough relative to Crescent City using the monthly mean sea levels.

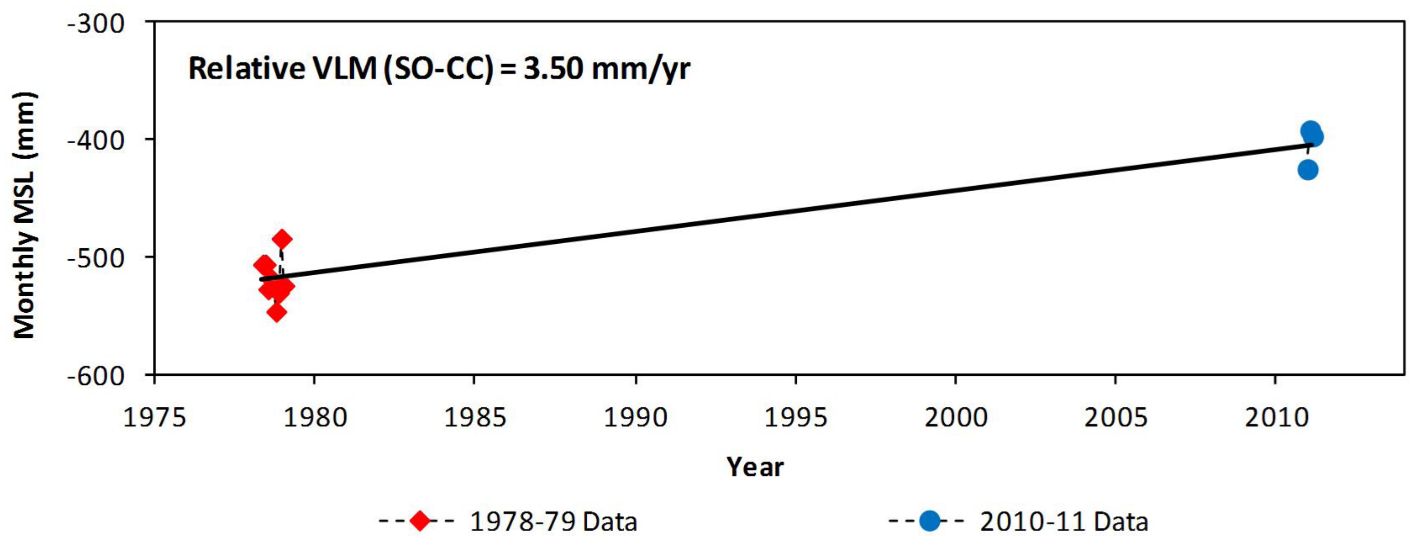


Figure 18. Differenced time series (Samoa minus Crescent City) representing the vertical land motion rate of Samoa relative to Crescent City using the monthly mean sea levels.

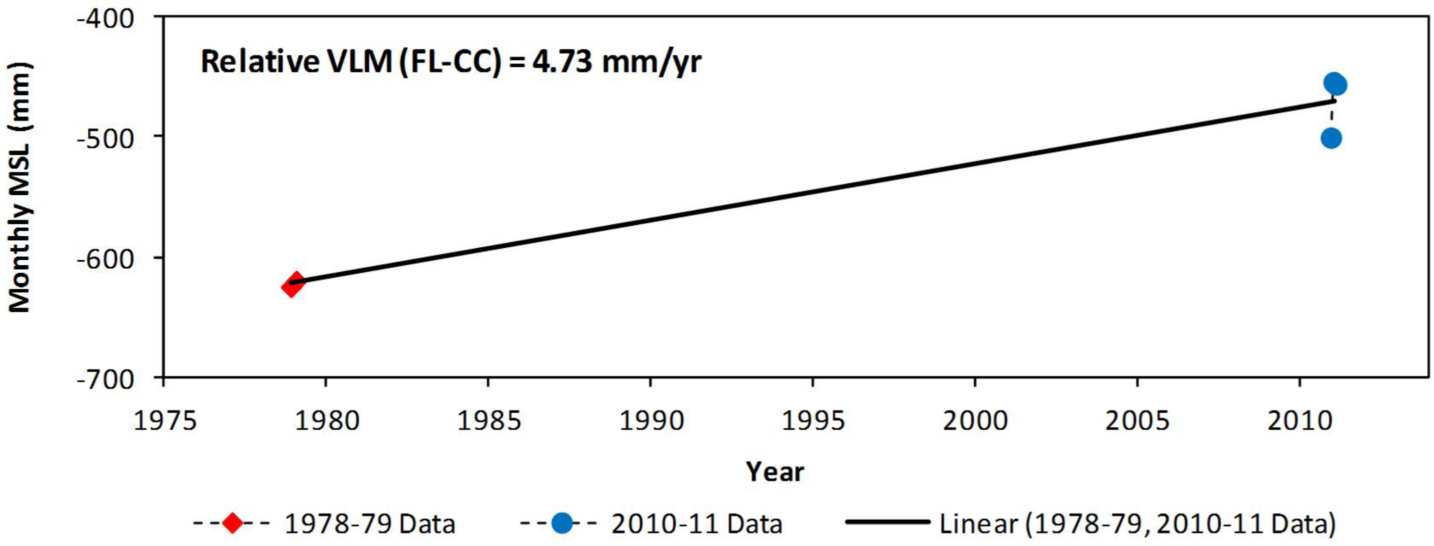


Figure 19. Differenced time series (Fields Landing minus Crescent City) representing the vertical land motion rate of Fields Landing relative to Crescent City using the monthly mean sea levels.

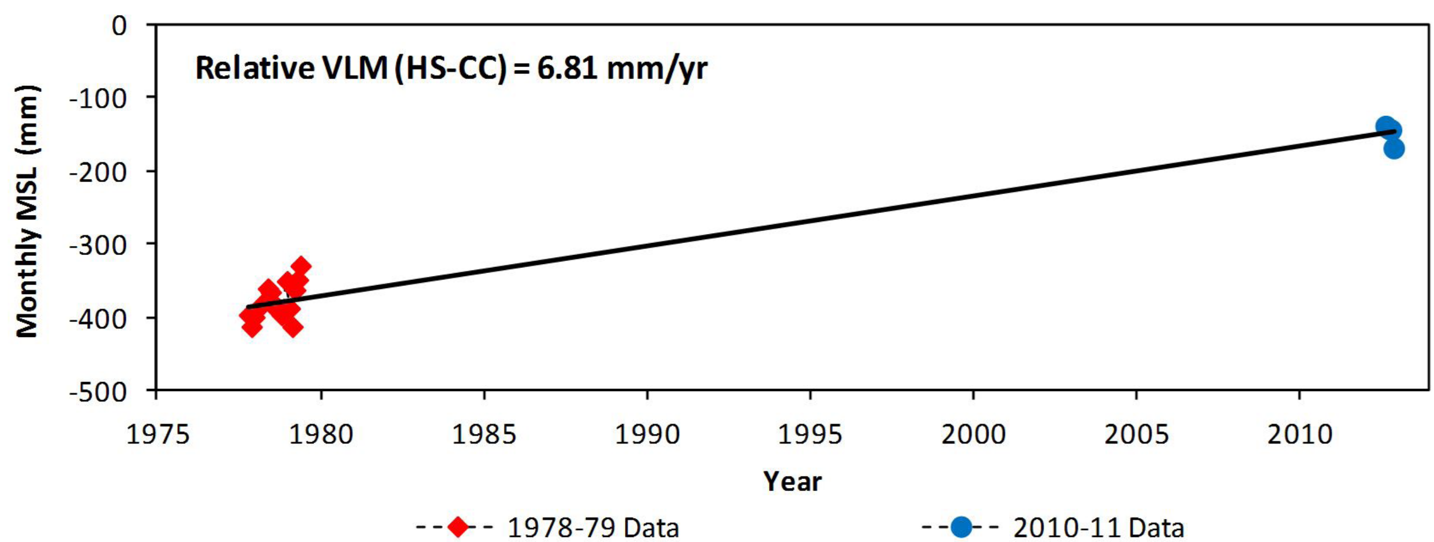


Figure 20. Differenced time series (Hookton Slough minus Crescent City) representing the vertical land motion rate of Hookton Slough relative to Crescent City using the monthly mean sea levels.

<u>Results Summary</u>

As stated earlier, the Crescent City tide gage is the longest available record for sea-level observations in the region. Using the available data and a regional estimate of regional sea-level rise (Burgette et al., 2009), we determined absolute motion of each tide gage location in this study and compare that to the available benchmark land level and GPS-derived land motion estimates .

Table 2 summarizes the rate trend statistics for CC, NS, and NS minus CC. For this assessment, the rates are determined from the annual summer water levels. The RSLR rate for CC is -0.97 mm/yr and assuming a regional eustatic sea-level rate of 2.28 mm/yr (Burgette et al., 2009) gives a VLM estimate of 3.25 mm/yr (**Table 2**). The RSLR and VLM rate estimates for NS are determined by using the 5.58 mm/yr relative VLM rate for NS minus CC (**Fig. 15**), which provides a VLM and RSLR rate of -2.33 mm/yr and 4.61 mm/yr, respectively (**Table 2**).

Using this same method, 1970's era and contemporary (2008, 2010, 2012, 2016) tidal observations are differenced from CC for the remaining tide gage stations (MRS, SO, FL, and HS) in Humboldt Bay and Trinidad (TR). Rates of local sea-level rise at temporary tide gage locations MRS, SO, FL, HS, and TR are, 3.39, 2.53, 3.76, 5.84 , and 3.15 mm/yr, respectively. Rates of local land-level change at MRS, SO, FL, HS, and TR are -1.11, -0.25, -1.48, -3.56 and -0.87 mm/yr, respectively (**Table 2**).

The general trend of vertical land motion in Humboldt Bay is manifested as greater subsidence in the south at HS near Table Bluff and the Little Salmon fault zone, decreasing towards the North in Arcata and Trinidad, nearly coincident

Table 2. Humboldt Bay Vertical Land Motion Estimates

Tide Station (TS)	Note	Datum	SLR§ and VLM* Rates (mm/yr)				Recommendation
			ReSLR #	RSLR †	TS-CC	VLM	
Crescent City (CC)	Long Term Tide Station with Mean Monthly Seasonal Cycle Removed	STND	2.28	-0.97		3.25	Did not change.
North Spit (NS)	Reference Humboldt Bay Tide Station with Mean Monthly Seasonal Cycle Removed	STND	2.28	4.61	5.58	-2.33	Did not change.
Mad River Slough (MRS) North Station data (5 months complete data)	Minor Tide Station	STND	2.28	3.53	4.50	-1.25	JKA recommends not using this estimate since NHE North Station is upstream of NOAA Mad River Slough tide gage site (previous VLM estimates based on this station).
Mad River Slough (MRS) South Station data (2 months complete data)	Minor Tide Station	STND	2.28	3.39	4.36	-1.11	JKA recommends using this estimate, which is based on NHE South Station located at the NOAA Mad River Slough tide gage site. However, only 2 full months of data is available for VLM estiamte.
Mad River Slough (MRS) South Station with estimated data from North Station relation (5 months complete data)	Minor Tide Station	STND	2.28	3.43	4.40	-1.15	JKA recommneds not using this estimate, good for check. This estimate is for NHE South Station that uses a 5 month tide series consisting of 2 month South Station data and 3 months estimated data from North Station relation.
Samoa (SO)	Minor Tide Station	STND	2.28	2.53	3.50	-0.25	Updated using NOAA published MSL values. NOAA recenlty published Towill observed data. NOAA published 3 recent monthly MSL values, and Towill had 3 MSL values. MSL values within 1mm of each other. Same VLM value with NOAA or Towill data.
Fields Landing (FL)	Minor Tide Station	STND	2.28	3.48	4.45	-1.20	JKA recommends not using. Original estimate using Towill data.
Fields Landing (FL)	Minor Tide Station	STND	2.28	3.76	4.73	-1.48	JKA recommends using. NOAA recently published monthly MSL values using Towill observed data, but shortened the record. NOAA published 3 recent monthly MSL values, while Towill had 4 MSL values. MSL values within 1 mm of each other.
Hookton Slough (HS)	Minor Tide Station	STND	2.28	5.83	6.80	-3.55	JKA recommends not using. Monthly MSL estimates were based on the 6-min record.
Hookton Slough (HS)	Minor Tide Station	STND	2.28	5.84	6.81	-3.56	JKA recommends using. JKA updated the MSL record for the recent Hookton occupation. Current monthly MSL values based on 1-hr record (NOAA standard approach). The previous MSL estimates were based on the 6-min record.
Trinidad (TR)	Minor Tide Station	STND	2.28	3.15	4.12	-0.87	JKA recommends using as draft VLM. Estimate based on NOAA published monthly MSL record for Trinidad. Period of record is 1972-87, and record with Crescent City is 129 MSL observations.

§ SLR = sea-level rise rate

* VLM = vertical land motion

\# ReSLR = regional sea-level rise rate

† RSLR = relative sea-level rise rate

with the SW-NE trend of the down-dip trend of the subducting Gorda plate. The Humboldt Bay and Trinidad regions are part of the on-land portion of the accretionary prism to the southern CSZ and, in the past, have demonstrated strong seismogenic coupling with the subducting Gorda plate with respect to observed deformation of CGPS stations on-land moving coseismically after moderate (>6.0) Gorda intraplate seismic events.

Benchmark Leveling

In the Humboldt Bay area leveling was completed between the NS tide gage and the main leveling route along Highway 101 in 1945, 1968, and 1988. Vertical land motion rates are listed in **Supplemental File S 1.** Relative uplift rates calculated from these epochs are all consistent within estimated random error, showing subsidence of North Spit at approximately 3 mm/yr relative to Arcata, and 1.5-2 mm/yr relative to benchmarks in the Old Town of Eureka (**Fig. 21**; Burgette et al., 2012). Uplift rates estimated from 1988-1968 leveling epochs are also consistent with the relative tidal rates between NS and CC as discussed in the previous section.

There are discrepancies involving data observed in 1931, which could be evaluated with a misclosure analysis (an analysis that could estimate the accumulated errors generated during level surveys; also called a closure analysis). We use the relative uplift rate between the NS primary benchmark and Benchmark 60 (in Eureka), estimated from the 1988-68 epoch difference, to estimate the portion of NS to CC route not observed in 1931. When evaluated against the random error estimates, the relative difference in uplift rate between Eureka and Crescent City involving the 1931 surveys are much lower than what is observed from the tidal records. Similarly, uplift rates calculated from 1988-1931 along the route east from Arcata show a concave-up decay inland similar to what is observed to the north in Oregon (Burgette et al., 2009; their fig. 8) but a strong subsidence (< -4 mm/yr) of the interior of area near Redding. In light of these discrepancies, we conclude that there may have been a systematic error that accumulated in the 1931 surveys in this area. Loop misclosure analysis may provide additional evidence of a problem localized in the 1931 epoch. Until that analysis is completed, we will not use data from the 1931 survey.

GPS

In some cases, the 1999-2016 GPS derived rates of motion (the "geodetic solutions") agree with the patterns of subsidence and uplift from the leveling surveys, particularly at HS, TR, and CC (**Fig. 22**). Results are presented in **Table 3.**

Continuous GPS stations operating (1999-2016) in Crescent City, Trinidad, Arcata (HSU), and Table Bluff confirm the vertical land motion inferences derived from sea-level and benchmark survey observations in this study and provide an independent quality control on the absolute motion of the land over historic time periods. GPS site vertical and horizon-

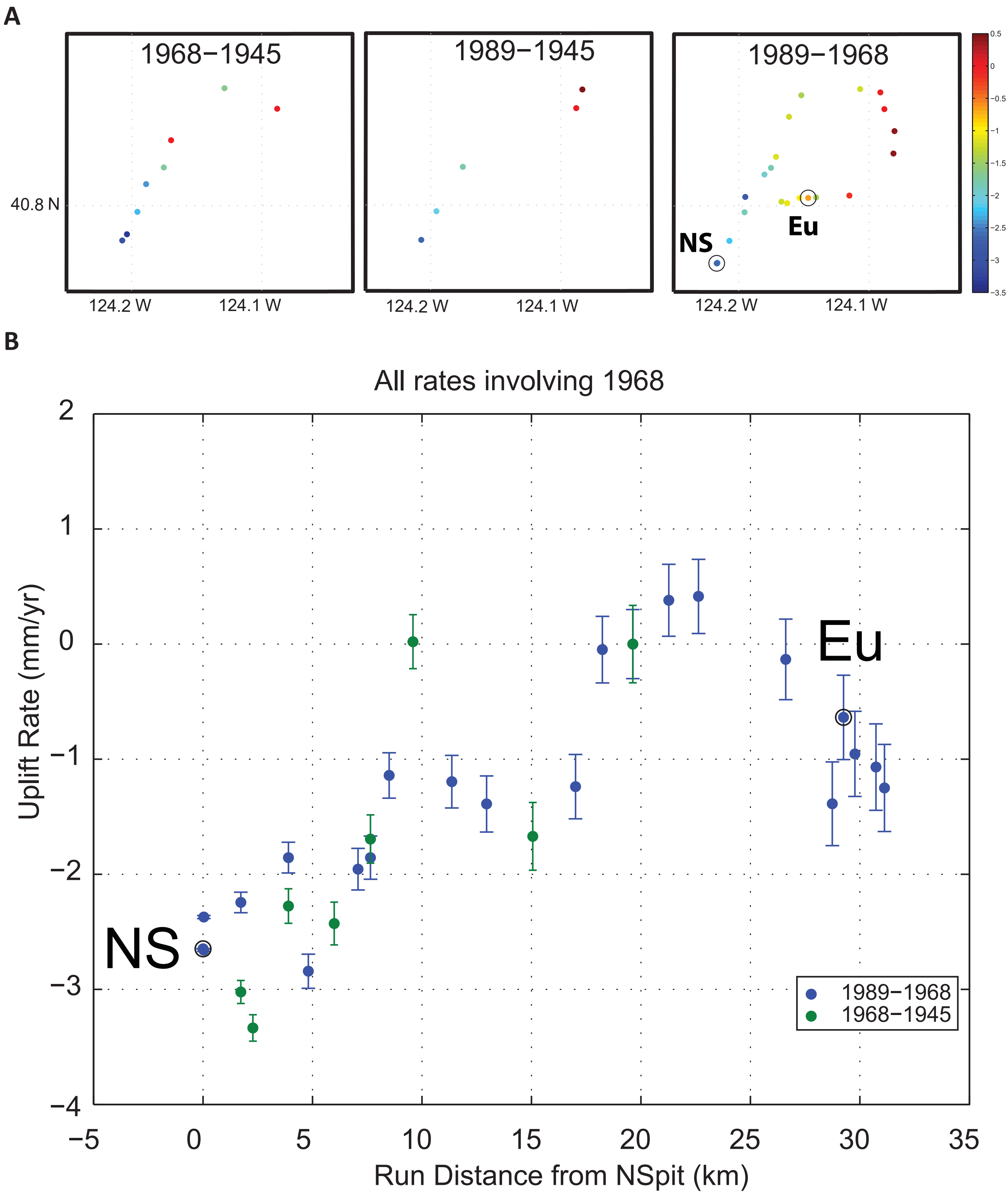


Figure 21. Benchmark Level Analyses Results. A. 1945, 1968, and 1989 benchmark leveling results plotted for central and northern Humboldt Bay (Burgette et al., 2012). Color represents vertical land motion rate in mm/year. Eu and NS benchmarks are circled. B. Vertical land motion rates (mm/yr) for all rates that include the 1968 survey. Eu and NS benchmarks are circled.

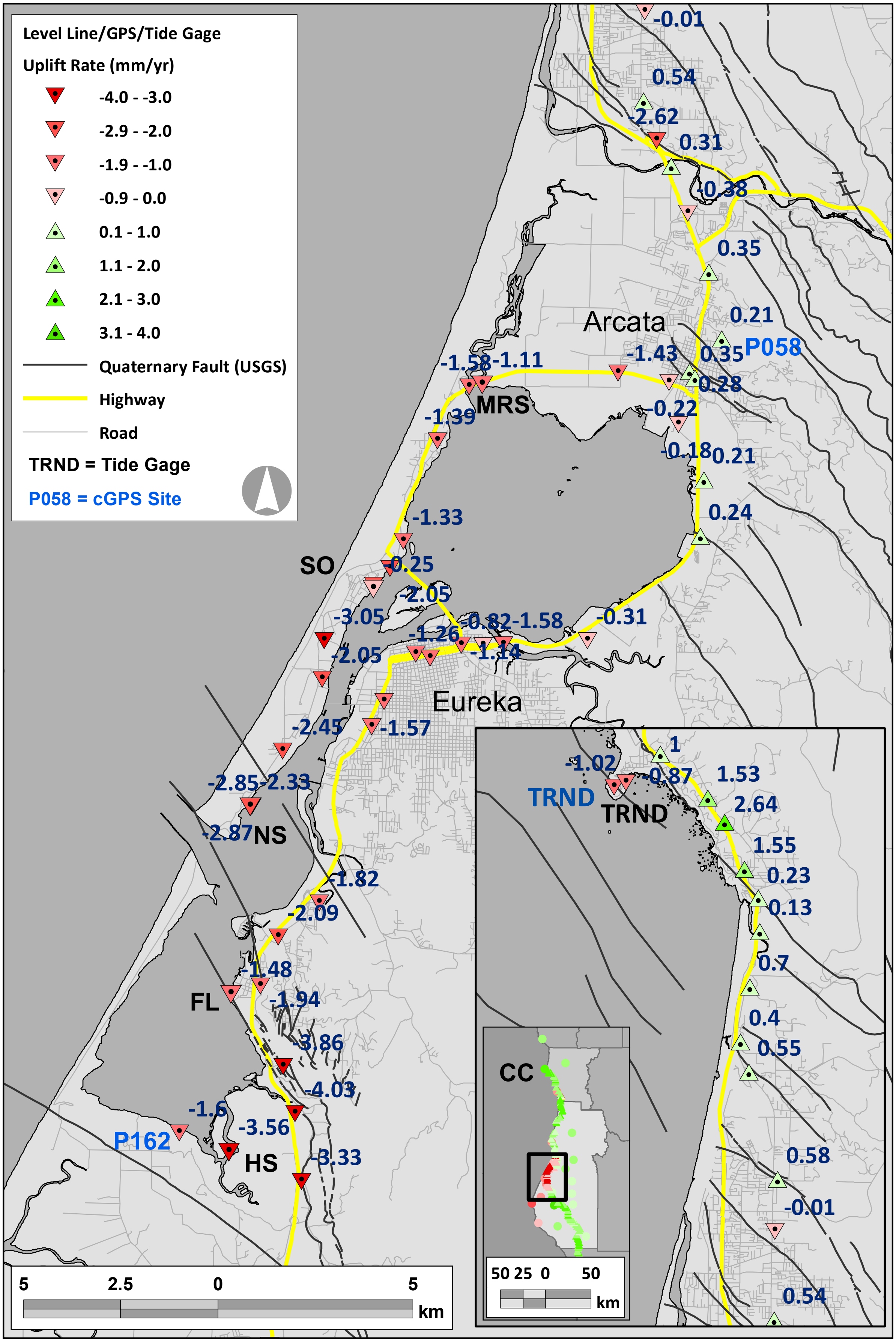


Figure 22. Summary of vertical land-level change in the Humboldt Bay region.

tal positions (the location of the GPS site) are shown for Crescent City (PTSG), Trinidad (TRND), Arcata (P058), and Table Bluff (P162) in **Figure 12**. For each GPS site, there are three panels, each with time (in years) on the horizontal axis. The upper panel shows the relative position in a North-South reference frame. If the trend moves upward (the positive direction), the GPS site is moving northward. The center panel shows the relative position in an East-West reference frame. If the trend is upward (the positive direction), then the GPS site is moving eastward. The lower panel shows the relative position in a vertical reference frame. If the trend is upward (in the positive direction), the GPS site is moving upwards vertically. We list the USGS published velocities (http://earthquake.usgs.gov/monitoring/gps/NCalifornia/ doi: 10.5066/F7NG4NRK) below each series of plots. From left to right is the velocity, uncertainty, and root mean square (RMS) uncertainty. The rates derived from these data are similar to the absolute differences displayed between the Crescent City and North Spit tide gages.

Table 3. Global Positioning System Data

Site Name	Source§	Latitude	Longitude	Beginning Observation	End Observation	Span (yrs)	North* (mm/yr)	Uncertainty (mm/yr)	East# (mm/yr)	Uncertainty (mm/yr)	Vertical† (mm/yr)	Uncertainty (mm/yr)
P179	USGS	42.098970	-123.685560	6/12/2007	7/22/2016	9.1	-3.5	0.3	-13.4	0.3	0.5	0.3
P734	USGS	42.076630	-124.293240	10/10/2007	7/22/2016	8.8	-1.8	0.3	-11.8	0.3	2.5	0.3
P786	USGS	41.845480	-123.980770	8/21/2008	7/22/2016	7.9	-2.5	0.4	-12.5	0.4	2.1	0.4
P154	USGS	41.807080	-123.360030	5/11/2007	7/22/2016	9.2	-3.9	0.3	-14.6	0.3	0.7	0.3
PTSG	USGS	41.782740	-124.255220	1/1/2003	7/22/2016	13.6	-0.6	0.3	-9.1	0.3	2.6	0.3
CACC	USGS	41.745600	-124.184300	9/27/2011	7/22/2016	4.8	-2.9	0.5	-11.2	0.5	4.1	0.5
P316	USGS	41.559130	-124.086160	7/1/2006	7/22/2016	10.1	-2.3	0.3	-12.8	0.3	-1	0.3
P155	USGS	41.272430	-123.188790	9/19/2007	7/22/2016	8.8	-4.1	0.3	-16.3	0.3	0.2	0.3
P325	USGS	41.151670	-123.882610	10/25/2006	7/22/2016	9.8	-2	0.3	-12.5	0.3	2.2	0.3
TRND	USGS	41.053890	-124.150880	11/16/1999	7/22/2016	16.7	3.3	0.2	-8.3	0.2	-0.9	0.2
P343	USGS	40.887120	-123.334190	6/21/2007	7/22/2016	9.1	-3.8	0.3	-17.2	0.3	0.3	0.3
P170	USGS	40.880230	-123.863300	5/28/2004	7/22/2016	12.2	-0.1	0.3	-13.1	0.3	2.3	0.3
P058	USGS	40.876310	-124.075390	11/10/2005	7/22/2016	10.7	4.1	0.3	-9.7	0.3	0.7	0.3
P169	USGS	40.791150	-123.967670	5/27/2004	7/22/2016	12.2	3.2	0.3	-10.5	0.3	1.7	0.3
P331	USGS	40.732910	-123.324130	6/21/2007	7/22/2016	9.1	-4.1	0.3	-18	0.3	0.5	0.3
P162	USGS	40.691090	-124.237050	9/11/2004	7/22/2016	11.9	8.2	0.3	-7.1	0.3	-1.5	0.3
P168	USGS	40.668640	-123.881480	9/15/2005	7/22/2016	10.9	2.4	0.3	-12.8	0.3	1.3	0.3
P161	USGS	40.637360	-124.213100	5/7/2005	7/22/2016	11.2	7.6	0.3	-9.5	0.3	-0.9	0.3
P326	USGS	40.575310	-123.698950	5/19/2006	7/22/2016	10.2	-2.9	0.3	-17.5	0.3	0.9	0.3
P160	USGS	40.551250	-124.133290	5/5/2005	7/22/2016	11.2	8.3	0.3	-12.7	0.3	0.6	0.3
P167	USGS	40.543700	-123.880200	9/17/2005	7/22/2016	10.9	3	0.3	-15	0.3	0.7	0.3
P159	USGS	40.504790	-124.282800	10/26/2006	7/22/2016	9.7	13.8	0.3	-11.8	0.3	-1	0.3
P327	USGS	40.478860	-123.573060	5/2/2008	7/22/2016	8.2	-3.3	0.3	-19.6	0.3	0.5	0.3
CME6	USGS	40.441400	-124.396330	10/12/2007	7/22/2016	8.8	19.6	0.3	-16.1	0.3	-2.9	0.3
P166	USGS	40.435180	-123.862850	11/2/2005	7/22/2016	10.7	3.9	0.3	-17.2	0.3	0.9	0.3
P158	USGS	40.422490	-124.107230	8/7/2004	7/22/2016	12.0	10.1	0.3	-16.2	0.3	3.1	0.3
P324	USGS	40.256840	-123.655760	5/17/2006	7/22/2016	10.2	1.8	0.3	-22.8	0.3	0	0.3
P157	USGS	40.247550	-124.308090	5/11/2006	7/22/2016	10.2	21	0.3	-30.4	0.3	0.6	0.3
P165	USGS	40.245550	-123.853280	6/9/2006	7/22/2016	10.1	5.6	0.3	-23.1	0.3	1.1	0.3
P163	USGS	40.219570	-124.057310	6/7/2006	7/22/2016	10.1	12.3	0.3	-26.2	0.3	1.9	0.3
P164	USGS	40.119260	-123.693360	8/10/2004	7/22/2016	12.0	3.3	0.3	-26.5	0.3	0.3	0.3
P156	USGS	40.024440	-123.906130	6/9/2006	7/22/2016	10.1	12.1	0.3	-31.7	0.3	-0.9	0.3

§ USGS GPS data sourced from http://earthquake.usgs.gov/monitoring/gps/NCalifornia/
* Rate of north-south motion relative to ITRF08. Positive values denote northward motion and negative values denote southward motion.
# Rate of east-west motion relative to ITRF08. Positive values denote eastward motion and negative values denote westward motion.
† Rate of vertical motion relative to ITRF08. Positive values denote upward motion and negative values denote downward motion.

Data Discussion

Across the region, Humboldt Bay is subsiding while the surrounding areas are not (**Fig. 22**). The subsidence originally interpreted to be locally observed at NS is now found to extend over a 100 km^2 area in the Humboldt Bay region (**Fig. 22**) and extends north to Trinidad, California (**Fig. 23**).

Spatial Variation of VLM

We compare vertical rates of motion derived from land-level surveys with those derived from our tide gage analyses in **Table 4** by differencing the benchmark VLM rates for the benchmark sites nearest each tide gage. Land-level derived uplift rates from 1968-1988 generally agree to within 1 mm/yr of tide gage derived rates for permanent and temporary sites within Humboldt Bay (1977-2016), with TR and SO having greater residual rates. We also difference the GPS VLM rates from the GPS sites nearest each tide gage (**Table 4**). There has been a cGPS at the CC tide gage station, but it has a temporally short record so we cannot use these data to evaluate VLM rates. This will be an important data set to include in future analyses, once the vertical uncertainty is reduced. TRND GPS data have a much lower residual than the benchmark rate, probably because the benchmark site is not in proximity to the tide gage, while the GPS site is. Upon comparison, the benchmark nearest the MRS tide gage is much closer than the GPS site and the benchmark residual is lower. However for HS, the GPS site is closer in distance to the tide gage, but the GPS site is installed in bedrock and the HS tide gage and nearest benchmarks are located in a sedimentary basin. This may explain why the benchmark VLM rate is closer to the HS VLM rate. The SO tide gage VLM rate is much lower than other rates calculated elsewhere in Humboldt Bay and even lower than the rate at TR. However we do not have a way to test for the large variation in VLM between the SO tide gage and the benchmark rate. While there is minor variation in the Humboldt Bay region VLM rates, they are all in the same sense of motion.

Zervas et al. (2013) present results from their analyses of VLM using tide gage data and GPS data in northern California. The Zervas et al. (2013) tide gage and GPS based estimates for VLM at CC and NS are 2.38 and -3.43 mm/yr respectively which compares with our estimates of 3.25 and -2.33 mm/yr respectively. The Zervas et al. (2013) VLM estimates are based on a global sea level rise rate of 1.7 mm/yr while we use a rate of 2.28 mm/yr (which may be an underestimate when compared to the rate estimated using satellite altimetry of 3.35 mm/yr; Nerem et al., 2010). In addition, the Zervas et al. (2013) MSL trend is based upon a different calculation that incorporates an analysis of seasonal sea-level cycles, but compares closely to our estimate (-0.65 vs our estimate of -0.97 mm/yr for CC). If the Zervas et al. (2013) analyses incorporated the 2.28 mm/yr ReSLR rate, their VLM rate for CC would be 2.96 mm/yr which is closer to our estimate of 3.25

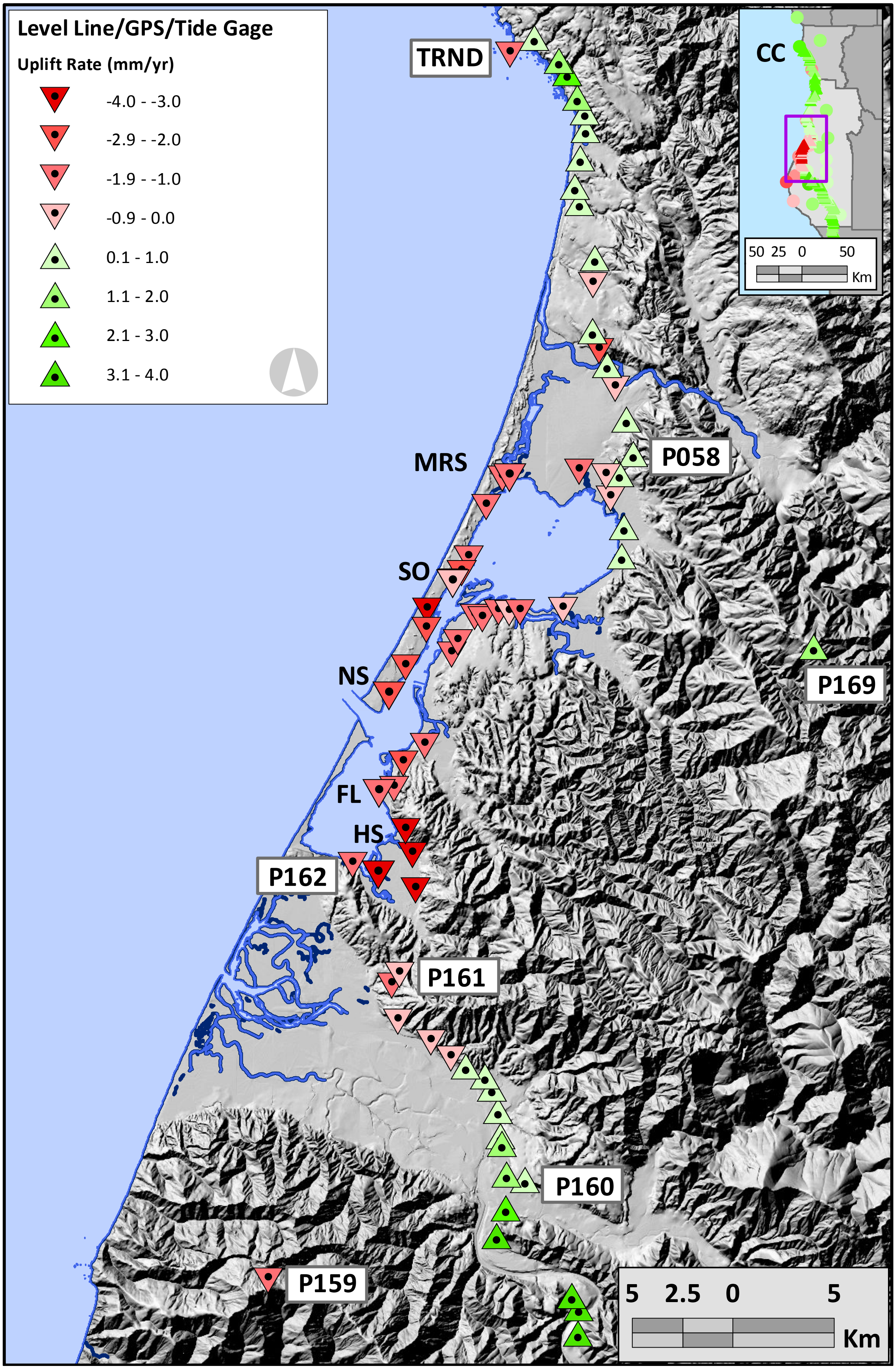


Figure 23. Summary of vertical land-level change in coastal northern California.

mm/yr. Zervas et al. (2013) also compared estimates of VLM between NOAA tide gage data and JPL GPS data for CC and calculated a GPS VLM rate of 2.51 mm/yr. This is comparable to the rate that we use for PTSG, 2.6 mm/yr (**Table 3**).

Sources of Spatial Variation

Sources of variation in VLM rates may be due to site stability, regional or local sediment compaction/subsidence, glacial isostatic adjustment (GIA), or tectonics including factors from the CSZ, upper plate accretionary prism faults, and earthquakes in the region.

NOAA conducts site stability surveys for the tide gage sites, so side stability is not a source for variation in the tidal data. Likewise, since the GPS sites are installed in bedrock, their data are not affected by long term site stability. However, this cannot be said for the benchmark site data.

There is evidence for and against sourcing uplift rate variation to the underlying basement material (bedrock versus fill/ bay margins). In the South Bay area, tide gage and benchmark sites have higher rates than the bedrock sites. This may be due to regional sediment compaction/subsidence. However, in the Eureka/Samoa area, there is more variation for sites within sedimentary basin sites than between those sites and adjacent bedrock sites (**Fig. 22**). However, the sedimentary basin sites are slightly higher than the bedrock sites. This may also be due to regional tectonics if the east-west variation in VLM rates were due to seismogenic coupling along the megathrust.

Following the last glacial maximum, isostatic rebound has caused a viscoelastic response from the crust and mantle. The post glacial vertical movement of the crust is driven by the removal of ice in various regions causing uplift and the placement of seawater in the oceans causing subsidence (Peltier, 1990, 2002; Stammer et al., 2013). This isostatic control to regional sea level may contribute to the rates observed in northern California (King et al., 2012), but it probably does not contribute to the variation at the scale of tens of kilometers.

Table 4. Land-level misfit between ntide gages with nearest benchmark and GPS data.

Tide Gage	Tide Gage Based Land-level (mm/yr)	Nearest Benchmark Land-level (mm/yr)	Residual Land-level Misfit (mm/yr)	GPS Site	GPS Based Land-level (mm/yr)	Residual Land-level Misfit (mm/yr)
CC	3.25	2.33	0.92	PTSG	2.6	0.65
TR	-0.87	1.53	-2.40	TRND	-0.9	0.03
NS	-2.33	-2.69	0.36			
MRS	-1.11	-1.58	0.47	P058	0.70	-1.81
SO	-0.25	-2.15	1.90			
FL	-1.48	-1.94	0.46			
HS	-3.56	-3.68	0.12	P162	-1.5	-2.06

Earthquakes in the region have caused observable offsets in GPS positions (**Fig. 12**). These coseismic offsets may contribute to offsets of VLM rates for the other two data sets, but may not be observable for the sites that are not continuously operating (e.g. the benchmark surveys and MRS, SO, FL, and HS tide gages).

Tide gage RSL and VLM estimates show a regional trend that is spatially variant in ways that are likely related to tectonics, regional sediment compaction/subsidence, or some other site factor. Given the variation in the regional trends visualized in Figure 23, along with the similarity in trends across geologic and site boundaries, there is still a trend that is most likely related to interseismic CSZ tectonic deformation. We suggest the locked portions of the southern CSZ are likely further east (down-dip) than currently recognized (e.g. Hyndman and Wang, 1995; Flück et al., 1997; Wang et al., 2001, 2003; Wang et al., 2007) and pose a significant seismic hazard for the Humboldt Bay region (Fortuna, Eureka, Arcata, CA). Numerical modeling must be conducted to test the hypotheses about the sources of tectonic control for VLM in northern California. This modeling will need to include fault geometry related to the CSZ and for the crustal faults in the region (i.e. the McKinleyville fault, a splay in the Mad River fault zone; Kelsey and Carver, 1988).

Contractual Results and Discussion

We here present an assessment of our objectives and how we were able to meet these objectives.

Tide Gage Deployment

Proposed Work:

We proposed to deploy between 3 and 6 temporary tide gages at historic locations for periods of 6-9 months. These gages would be installed with site infrastructure that included stilling wells (stilling basin), staff plates, and power systems. These gages would be surveyed with high precision (first order) digital leveling equipment provided by Dr. Ray Weldon from the University of Oregon (UO). We proposed to cooperate with the Army Corps of Engineers to obtain water-level data from observations at historic tide gage locations at Fields Landing and Samoa.

We proposed to install a permanent tide gage at the Trinidad Pier in cooperation (and possibly funded by) the Trinidad Rancheria. We proposed to find additional sites to install tide gages south of the Humboldt Bay area in the King Range or Shelter Cove areas.

Completed Work:

We deployed temporary tide gages at 2 historic tide gage locations (Mad River Slough and Hookton Slough) and are installing a permanent tide gage at the Trinidad Pier. We conducted first order level surveys to the tide gage installations.

We used the UO equipment for the Hookton Slough site and we rented level survey equipment for the other surveys because the UO equipment was no longer available. We acquired water surface elevation data from Towill Surveying, Mapping, and GIS Services (ACOE) for the Fields Landing and Samoa tide gage locations. The third tide gage site was the Chevron Dock in Eureka. We installed a stilling basin at this site but were unable to install a tide gage because our partner CENCOOS (Central and Northern California Ocean Observing System) installed instrumentation in our stilling basin during a change in personnel (the new personnel was unaware of our agreement).

We purchased tide gage equipment to install as both temporary and permanent installations. One permanent installation will be at the USFWS National Wildlife Refuge, Salmon Creek Unit. We will first need to acquire funding for this installation. We have a preliminary agreement with Eric Nelson, the Refuge Manager, to cooperate during the installation and management of this gage.

Level Surveys

Proposed Work:

We proposed to obtain historic level survey data from 7 surveys conducted between 1931 and 1992. We proposed to conduct first order level surveys, using the digital level from UO. We proposed to collaborate with the California Department of Transportation (CalTrans) District 1 to re-level their NAVD88 line.

Completed Work:

We obtained historic level survey data from the National Oceanic and Atmospheric Administration (NOAA) Central Library archives for surveys conducted in 1931, 1944, 1967, and 1988. We used survey data from three surveys, 1944, 1968, and 1988. The 1931 and 1944 surveys incorporated systematic vertical position error and were not included in our analyses.

We conducted first order level surveys between benchmarks and the tide gage locations for the Hookton Slough, Mad River Slough, and Trinidad Pier sites. We did not conduct surveys for the Fields Landing nor Samoa sites because those observations were made by another entity (Towill).

Education and Outreach

Proposed Work:

We proposed to work closely with academia at the University of Oregon and Humboldt State University. We proposed that we would make regular updates to the local ecosystem science and planning community through the Humboldt Bay

Initiative (HBI) working group meetings, briefings to the Humboldt County Public Works and Planning Departments, the HSU Geology colloquium seminars which are open to the public, the Harbor District's Humboldt Bay Symposium, and presentations to the Humboldt Friends of Geology (HFOG) semi-annual meetings. We planned on having students and/or team members present our results at a scientific conference such the Geological Society of America or American Geophysical Union annual meeting.

Completed Work:

We worked with Dr. Ray Weldon from the University of Oregon and Drs. Mark Hemphill-Haley and Jason R. Patton at Humboldt State University to incorporate student volunteers into our level surveys. This provided an opportunity for these students to develop an interest in estimating future sea-level change in northern California, as well as how tectonics contribute locally to these observations.

During the project timeline of Phase I, the USFWS requested that we prepare materials for a field trip to visit the locations where our tide gage observations were made. There was also a request to prepare and present a webinar summarizing the results from this project.

Local Presentations: We presented project status updates at several HBI meetings (10/21/2010, 1/27/2011, 9/20/2013, 11/3/2013, 6/26/2014, 12/8/2014, and 8/20/2016). Digital presentation files for these HBI meetings are posted online here: http://www.hbv.cascadiageo.org/?page_id=183.

- We presented an educational poster about our project at the 2011: Humboldt's Ready Natural Hazards workshop http://cascadiageo.org/posters/humboldts_ready_2011_RSL.pdf.
- We presented the ecological impacts of sea-level rise in the Humboldt Bay at the 2012 Humboldt Bay Symposium http://www.hbv.cascadiageo.org/HumBayVert/presentations/HBS_2012_presentation_THL.pptx
- We presented our results and research project to CalTrans in 2014 http://www.hbv.cascadiageo.org/HumBayVert/presentations/CalTrans_HBV_presentation_2014.pptx.
- We presented our results at the inaugural "Cascadia Presents" event on 10/23/2015 http://presents.cascadiageo.org/?page_id=17.
- We presented our results at the April 2016 "Science on Tap, Humboldt" on 4/6/2016 http://earthjay.com/?page_id=3894.
- We presented our results at the Friends of the Arcata Marsh event at the Arcata Marsh Interpretive Center on 7/22/16 http://earthjay.com/?page_id=4086. Videos and digital presentation files from these public presentations are posted online.
- We presented our results at the Humboldt Bay Symposium on 10/21/2016

Scientific Meetings: We presented the results from our research at the following meetings. Posters and digital presentations are posted online for these meeting presentations here http://www.hbv.cascadiageo.org/?page_id=183.

- 2011: American Geophysical Union Annual Meeting http://cascadiageo.org/posters/patton_etal_2011_agu_rsl_vs_tectonics.pdf
- 2012: Humboldt Bay Symposium http://www.hbv.cascadiageo.org/HumBayVert/presentations/HBS_2012_presentation_THL.pptx
- 2012: National Science Foundation GeoPRISMS workshop (the poster won the student poster award) http://earthjay.com/posters/patton_leroy_2012_geoprisms_csz.pdf
- 2015: Seismological Society of America annual meeting http://cascadiageo.org/posters/patton_etal_2015_SSA_vertical_tectonics.pdf

Field Trip and Webinar:

- We led a field trip to the tide gage locations on August 26, 2016. A map and a field trip guidebook are posted on the HBV website. http://www.hbv.cascadiageo.org/?page_id=370
- We presented the results of the Phase I part of this project to the Humboldt Bay Initiative meeting. The meeting was broadcast as a teleconference and video documented. The video of this presentation, along with the digital presentation file, is located online on the HBV website and on YouTube. http://www.hbv.cascadiageo.org/?page_id=342

Timeline

Proposed Work:

- Conduct survey to NAVD bench marks and existing level lines: Oct. 2011 – continue as needed Apr. 2012
- Compile existing leveling data: Oct. 2011
- Collect tide gage data and maintain equipment: Oct. 2011 – Apr. 2012
- Analyze data: Jan. 2012 – May 2012
- Report on results: Sep., 2012

Completed Work:

Conduct survey to NAVD bench marks and existing level lines: Oct. 2011 – continue as needed Apr. 2012: We did not complete this task because it was cost prohibitive. The cost estimate from CalTrans was approximately $100,000 for this task, which was more than the complete budget for this project. This task would have resulted in a more recent evaluation of benchmark vertical positions that were last surveyed in 1988. The results from this analysis would have brought the independent tide gage and GPS observations into the same time period as the benchmark position observations. Currently, the GPS and tide gage observations are from the period of 2008-2016 while the most recent benchmark level survey is from 1988. While the vertical land motion rates probably did not change much over this time period, we won't know the significance of this until these data are collected. Compile existing leveling data: Oct. 2011: We completed this task on March 12, 2012.

Collect tide gage data and maintain equipment: We are continuing to collect tide gage data and maintain the equipment.

- Hookton Slough (HS): gage deployed August through November, 2012
- Mad River Slough (MRS): gage deployed July through August 2016
- Fields Landing (FL): gage deployed December 2010 through March, 2011
- Samoa (SO): gage deployed December 2010 through February, 2011
- Trinidad (TR): gage deployed August, 2016

Analyze tide gage data: Data analyses began in 2011 and was completed in August 2016.

Report on results: Reports and updates were provided to the USFWS on 12/31/2014, 4/3/2015, 3/22/2016, and 8/15/2016. We present our final report in this document (2/17).

GIS products: We compiled the tide gage, benchmark, and GPS data as point shapefiles in 8/2016. These data are published on the HBV website. http://www.hbv.cascadiageo.org/?page_id=120

Budget

Proposed Work:

We present the original budget in **Supplemental File S 2.**

Completed Work:

We present the final budget in **Supplemental File S 3.** Final budget reflects adjustments for contract working, equipment purchases & installation, and additional data analyses as we modified our work plan during the project.

Future / Ongoing Work

The findings in this final report are composed from content included in a paper draft that we are preparing to submit to Geophysical Journal International. Following the completion of this Phase I, we are preparing for Phase II of this project. Phase II includes the following goals.

We will be working with Eric Nelson at the Humboldt Bay National Wildlife Refuge (HBNWR) to install a semi-permanent continuous tide gage at the Hookton Slough location. First we will develop agreement between our group and the

Humboldt Bay National Wildlife Refuge to define our roles. We have already acquired the tide gage instrumentation with funding from Phase I. This installation will have a cellular based uplink to the internet where we will serve the data in real time. We hope to create an educational kiosk at the visitor center where people can learn about sea-level rise and the regional tectonics in the Humboldt Bay area.

We will work with Humboldt State University to install a tide gage at the Chevron Dock in support of CENCOOS. The data from this gage will be served on the internet via the CENCOOS website. We will cooperate with students from HSU, CR, and local high schools to conduct high precision surveys for this tide gage installation.

We will be working with UNAVCO, Inc. to establish cGPS observations at the North Spit and the Hookton Slough tide gage sites. Collocating cGPS stations with tide gages provides an important independent measure of VLM and SLR (Woodworth et al., 2017).

We will be working with faculty and students from Humboldt State University (HSU) Department of Geology to conduct high precision level surveys for benchmarks in the Eel River valley west of Fortuna, California. We will also collaborate with student volunteers and Northern Hydrology and Engineering to install temporary tide gages at other historic tide gage locations in the Humboldt Bay area that include the Chevron Dock in Eureka, the Commercial Dock in Eureka, Hookton Slough (Humboldt Bay National Wildlife Refuge), the King Range Conservation District, Shelter Cove, and other locations around Humboldt Bay (e.g. Bracut Industrial Park).

We will use GPS data to constrain the locking on the Cascadia subduction zone in our study area. Later, we will model the tectonic deformation based upon these locking estimates. This tectonic modeling will predict the tectonic deformation between our observation sites and we will estimate the misfit between our model prediction and the observation data (benchmark level and tide gage data). This tectonic modeling will be the basis for a predictive raster GIS model that we will prepare for northern California. People would be able to use this raster to predict the VLM rates for positions between our observation sites (tide gage, benchmark, and GPS).

We are currently working to secure funding from a private donor to match potential funding from the California Seismic Safety Commission to prepare for Phase II of this project. Phase II will include the Chevron Dock installation, the HBNWR installation, the CGPS installation, and the level survey in the Eel River Valley.

Conclusion

We have utilized historic benchmark level data, GPS data, and water surface elevation observations from campaign and permanent tide gages to characterize the interseismic tectonic land-level change associated with the southern Cascadia subduction zone. This characterization is only for the positions included in these analyses, so needs to be further modeled before these observations can be projected to locations between our observations. We suggest the locked portions of the southern CSZ are likely further east (down-dip) than currently recognized (e.g. Hyndman and Wang, 1995; Flück et al., 1997; Wang et al., 2001, 2003; Wang et al., 2007) and pose a significant seismic hazard for the Humboldt Bay region (Fortuna, Eureka, Arcata, CA). We are currently working with a Ph.D. graduate student at the California Institute of Technology to conduct elastic modeling of the Earth's crust so that we can provide these estimates.

We do not attempt to provide analyses nor interpretation of the potential ecologic impact of sea-level rise, as modulated by regional tectonics. However, once the tectonic modeling is completed, ecosystem and resource managers may overlay the sea-level projection of choice onto our tectonically driven estimates of land-level change.

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Glossary

Biostratigraphic: The stratigraphic analyses based upon fossils and how the fossils change with stratigraphic depth.

Coseismic: The part of the earthquake cycle that occurs during the earthquake.

Dextral Shear: Plate tectonic shear that has a right-lateral strike-slip sense of motion, like that occurs along the San Andreas plate boundary fault system.

Elastic: A material that can return to its original shape after stress is applied or strain is released.

Eustatic Sea-Level: Sea level that is the result of a change in volume of water in the oceans, for example as a result of the glacial-interglacial cycle or from thermal expansion or contraction.

Glacial Isostatic Adjustment (GIA): The ongoing movement of land following (1) the melting of glaciers reducing the mass over continental lithosphere and (2) the melting of glaciers adding mass over oceanic lithosphere.

First-Order Leveling: High precision level surveys that have the highest precision standards in the Standards and Specifications for Geodetic Control Networks (1994).

Interseismic: The part of the earthquake cycle that occurs between earthquakes.

Isostatic: Equilibrium of the earth's crust as a balance between the downward forces of the crust and the upwards forces of the Mantle.

Lithostratigraphic: The stratigraphic analyses based upon how rock layers and sediment types and characteristics change with stratigraphic depth.

Megathrust: The subduction zone fault.

Misclosure Analysis: An analysis of survey data that could estimate the accumulated errors generated during level surveys; also called a closure analysis.

Paleogeodesy: The geodetic analysis of prehistoric land motions.

Run distance: The running horizontal distance accumulated during a level survey.

Sea level – regional: Global sea level applied to a regional scale.

Sea level – local: Global sea level modified by local processes that include effects like plate tectonic processes.

Seismogenic Coupling: The mechanical interaction between rocks on each side of a fault (Wang and Dixon, 2004).

Sonde: An instrument that automatically transmits information about its surroundings (e.g. water surface elevations).

Tidal Geometry: Geometric relations between the shapes of tidally formed geomorphic features and other measures that include the spatiotemporal variation in tidal elevations.

Viscoelastic: The property of materials that include both viscous and elastic properties. The mantle behaves with viscoelastic properties.

Viscous: Material properties that resist flow and strain linearly with time, when a stress is applied.

- Wang, K., and Dixon, T., 2004. "Coupling" Semantics and science in earthquake research in EOS, v. 85, Issue 18, p. 180.

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